Workshop on

Recent developments in small scale combustion devices

Arranged by:

Jaap Koppejan, TNO Science and Industry, Netherlands
Sjaak van Loo, Chess, Netherlands

October 21, 2005
Palais des Congres, Paris, France

Organised jointly by:

IEA Bioenergy

CombNet

ThermalNet/IEA Bioenergy Task 32
Recent Developments in small scale combustion devices
October 21, Paris, France

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Palais des Congres, Paris, France

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Report of the workshop

Introduction, Jaap Koppejan, IEA Bioenergy Task 32

Jaap Koppejan welcomed all participants and provided an introduction to the workshop, which was organised jointly by IEA Bioenergy Task32 (Biomass Combustion and Cofiring) and the Combustion task within the EU ThermalNet project (COMBNET).

IEA Bioenergy Task 32 has a global scope, with currently 12 members. Attention is paid to selected topics related to biomass combustion as well as cofiring. On the other hand, ThermalNet has a European scope, with a view on all thermochemical conversion technologies for biomass. Both networks have in common that they organise regular meetings and expert workshops to exchange knowledge and disseminate key technical and non-technical information on biomass combustion and cofiring.

This workshop presented some of the latest advances in combustion modelling tools, furnace design, combustion control systems, and flue gas cleaning systems to obtain high environmental performance and reliability for small scale combustion applications at minimum costs.

Driven by requests for lower emission limits (particularly pm10) and competition for increasingly reliable, efficient and cost effective combustion devices in a growing market, the technical and environmental performance of small scale biomass combustion devices is still improving. This is true for both domestic woodstoves, pellet and wood chip fired boilers.

This workshop, which was part of the 12th European Bioenergy Conference, was chaired jointly by Jaap Koppejan and Thomas Nussbaumer and was attended by approx. 30 participants.

Austrian pellet boiler technologies - state-of-the-art, ecological evaluation and future developments" Gerold Thek, Bios Bioenergiesysteme GmbH, Austria

Gerold Thek presented an overview of the growing Austrian pellet market and then focused on technology developments in geometry, control systems and boiler technology of small scale pellet combustion systems which have resulted in lower emissions, increased reliability and higher efficiency.

In the last 5 years, the market for pellet boilers in Austria has increased from approx. 2000 per year to approx. 6000 boilers today. The approx. 28.000 pellet boilers used for domestic scale central heating systems alone consume some 216 kton of pellets, in addition there is demand from pellet stoves and larger combustion systems. The 18 pellet producers have a total production of some 500 ktons pellets, the quality of which is regulated by ÖNORM standards for transport, transporation and storage. Similarly, the quality of pellet furnaces produced by some 30 manufacturers is regulated with the ÖNORM EN 303-5.

The combustion quality has improved significantly due to measures such as air staging, flue gas recirculation, automatic heat exchanger cleaning systems, CFD aided design and optimized positioning of secondary air nozzles, and finally improved control systems that guarantee low emissions at all load conditions.

Due to technical improvements, dust emissions of modern pellet furnaces could be reduced in the last 5 years from approx 10-25 mg/MJ to 7-12 mg/MJ today. As the remaining dust consists mainly of aerosols, this emission strongly depends on the composition of the fuel. Similarly, CO emission has gone in the past five years from typically 55 mg/MJ to 30 mg/MJ today.

Some important near future developments are in the areas of CFD aided combustion design, reduced aerosol emissions, integration with solar systems, as well as flue gas condensation. The first pellet boiler with flue gas condensation (effiency 103% on LHV basis) is already on the market. Finally, there is great interest in Austria for application of Stirling engines for wood chip and pellet furnaces. A few pilot plants of 35 and 70 kW are already in operation.

Assessment of factors affecting hazardous emissions from residential wood-burning appliances; Fernando Preto; CANMET Energy Technology Centre – Ottawa, Canada

Fernando Preto (senior research scientist at CANMET, Canada) presented the results of a recent study in which emission factors (particulate matter, VOC, Dioxins and Furans) for residential wood burning appliances were assessed.

Environment Canada has estimated that 14% of total national PM2.5 emissions and 15% from national VOC emissions are from residential combustion systems. However, apart from British Columbia where the government has adopted US standards, there are currently no requirements for wood burning appliances to meet any emissions criteria. For this reason the process has been recently initiated for a national emission regulation.

Emission measurements were performed at CANMET for three types of cordwood stoves (conventional old, conventional new and a certified stove) as well as a pellet stove under different operating conditions (fuels and load rate). The measurements showed wide variations, total PM emissions ranged from 0.019 g/MJ for the pellet stove operated at a high burn rate to 3.68 g/MJ for the “old” conventional stove operated at a low burn rate. Average emissions are 1.68 g/MJ for the conventional cordwood stove and 0.44 g/MJ for certified non-catalytic stoves. VOC emissions ranged from 0.02 - 13 mg/kg for pellet stoves, up to as high as 38 - 13,100 mg/kg for Cord Wood Stoves, these VOC’s are mainly benzene and toluene.

Key factors in bad combustion quality observed are related to stove design and transient state operation. Some stoves lack proper refractory lining, baffle and air staging. Higher emissions of CO, VOC and dust were observed for wood with increased moisture content (except for CO), lower firing rates (except for VOC) and use of softwood instead of hardwood.

A systematic process identification as a tool for combustion control design, Kai Pietila, VTT, Finland

Kai Pietila presented methods to perform systematic process identification as a tool for combustion control design. By performing emission measurements at different operation conditions of a 300 kW woodchip fired boiler, reproducible correlations were found for CO as a function of primary and secondary air ratio and heat load. Step response tests showed that first order models with dead time appropriately describe the dynamic behaviour.

Finally, the possibility was evaluated to use soft sensors for the estimation of O_2, CO_2, CO and heat output, using primary and secondary air and fuel power as input variables and the Takagi-Sugeno fuzzy model. A comparison of model results with actual measurements indicated that CO_2/O_2 can be modelled reliably, using temperature measurement data. The prediction of CO concentrations is less straightforward and will require more research.

A novel electrostatic precipitator (ESP) for residential combustion, Morten Berndtsen, the National Institute of Technology, Environment and Safety, Oslo, Norway

Morten Berndsen introduced the preliminary results of Clean Air, a European project in which a small scale Electrostatic Precipitator has been developed for domestic wood stoves. The project had a budget of approx. 1.2 M€ and was coordinated by APP (Norway) with industrial participation of Sereps(France), VUKOV (Slovakia), CSO (UK), ShroederPlast(Denmark), BK+K (Germany) and RTD partners TI (Norway) and PERA (UK).

The background for the development of the ESP was the recognition that domestic wood combustion, although being renewable, can have significant health costs due to the emission of fine dust particles (particularly PM2.5), which are associated with increased mortality and cardiovascular and lung disease. This is largely due to the transient operation of woodstoves; particularly during the start-up phase, high dust emissions occur.

A prototype of an electrostatic precipitator for end-of-pipe/chimney applications was developed and successfully tested under practical conditions in Norway. The ESP has a cleaning efficiency of 90-95% for particles above 0.1 μm. Typically it can collect up to 20 kg of dust, which limits manual cleaning of the unit to once per year. Electric power consumption is below 120 W.

The unit has an expected sales price of 400€. A case study on the avoided health costs for the inner city of Oslo (due to lower aerosol concentrations) indicated that this would be equivalent to a social payback period period of only year. However, as there are no financial incentives yet for private households to invest in small scale air cleanup, political commitment and financial incentives are needed is toachieve real environmental improvements and create a market for this environmental technology.

Conclusions and closing
PD Dr. Thomas Nussbaumer, Verenum, Switzerland

Thomas Nussbaumer concluded the session with a number of interesting observations. Firstly, small scale biomass combustion already has an important contribution to renewable energy production today, however also to harmful aerosol emissions. Technological developments in pellet combustion systems, better combustion control devices and particle removal sytesms have result in more efficient and cleaner combustion systems, however there are great geographic differences in performance of combustion technologies. Particularly for log wood combustion there is still a great need for improvement of systems available on the market today. Environmental performance can be improved by replacing low quality stoves by better stoves. In many cases this results in additional costs for the device.

Particularly for improvements that are beneficial mostly for society in terms of lower health costs, and have much less direct benefits for the owner/user, it is a government task to inform end-users to operate stoves properly, provide proper legislation enforcing quality standards on equipment sold, as well as incentives for further emission reduction using add-on technologies. This includes use of the proper fuel, which can also be established through standardisation.

Annex 1. Introduction,
Jaap Koppejan, IEA Bioenergy Task 32

Recent Innovations in Small Scale Combustion Devices

Chairpersons:
Jaap Koppejan, TNO, Netherlands
PD Dr. Thomas Nussbaumer, Verenum, Switzerland

Organised by

Biomass Combustion and Cofiring
IEA Bioenergy Task 32

CombNet
GasNet
PyNe

ThermalNet
PyNe/GasNet/CombNet

Workshop on small scale combustion devices

- Drivers:
  - High competition for even more reliable, convenient, clean, efficient and cost effective equipment
  - Lower emission limits
  - Great market expansion
- Contents today:
  - innovative boiler designs,
  - small scale ESP systems and
  - better control concepts

Agenda

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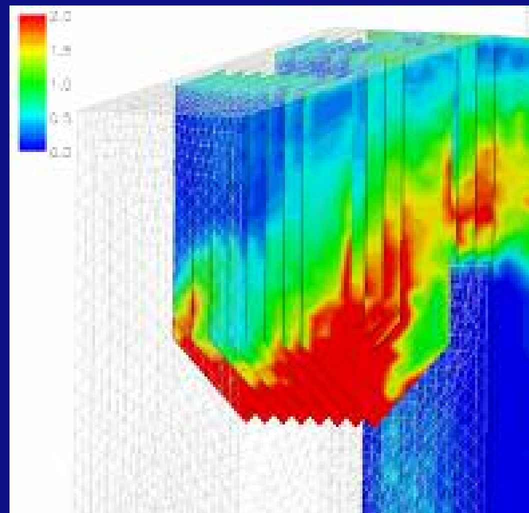
IEA Bioenergy Task 32

- Members

Australia	Netherlands
Austria	Norway
Belgium	Sweden
Canada	Switzerland
Denmark	United Kingdom
European Commission	Germany

- Aim

  Generating and sharing key technical and non-technical information on biomass combustion



- Activities

  Task meetings

  Workshops

  Specific studies

Current activities of IEA Bioenergy Task 32

- Global inventory of biomass cofiring
- SCR catalyst deactivation when cofiring biomass
- Aerosols from biomass combustion
- Handbook of biomass combustion & cofiring
- Striated flows in PC furnaces
- Annual efficiency determination of DH plants for simplified fuel accounting
- Public perception of biomass cofiring
- Ash related issues (deposition, corrosion)
- New biomass combustion based CHP concepts
- Innovations in small scale biomass combustion
- Development of methodology for Cumulative Energy Demand of biomass combustion systems

- More information: www.ieabcc.nl

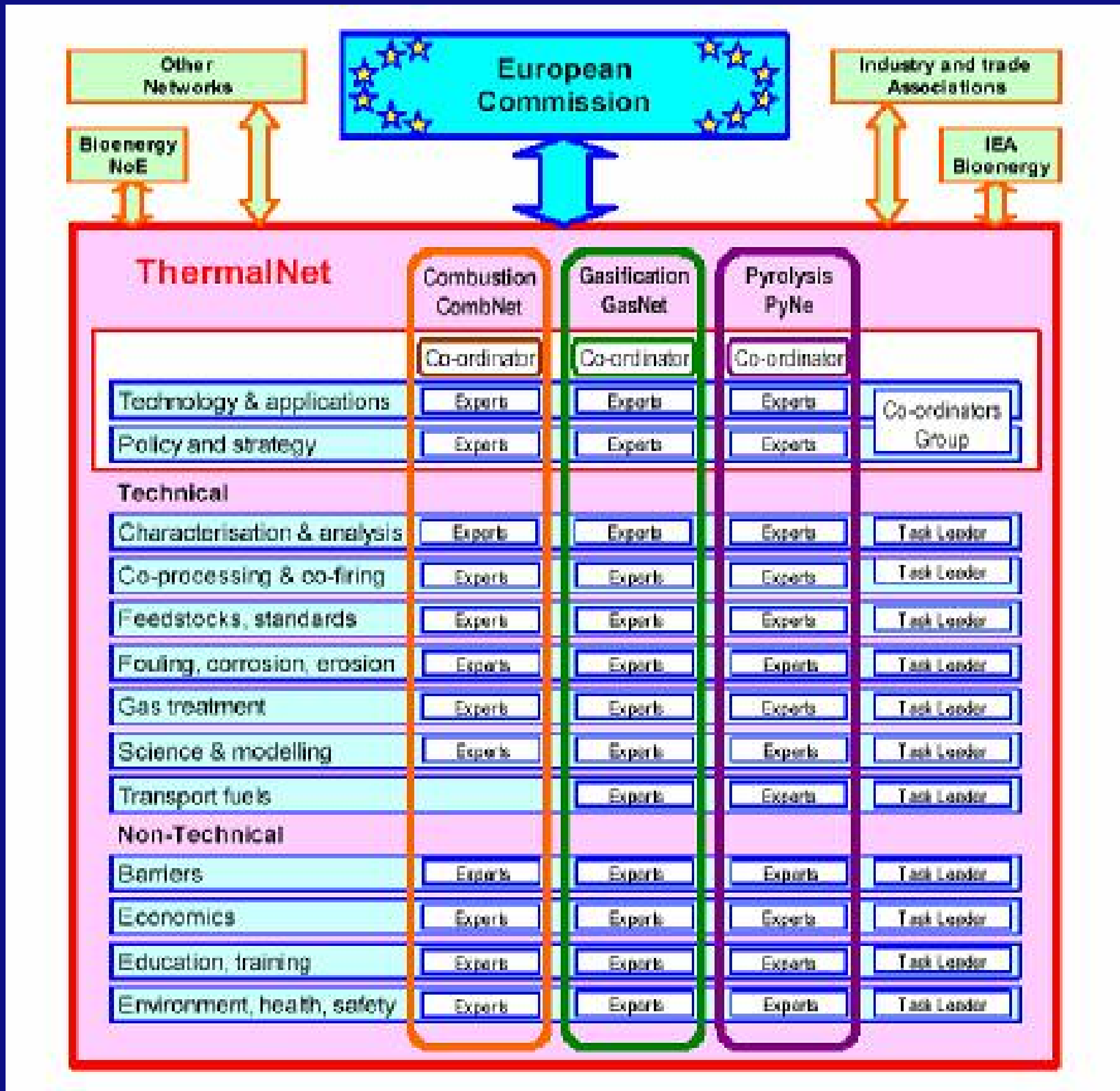
EC-ThermalNet

- European Network of approx 50 experts on thermal conversion of biomass

- Aim: Sharing expert information on thermal conversion of biomass

- 2 meetings per year
- Workshops
- Website
- Newsletters

- www.thermalnet.co.uk



Annex 2. Austrian pellet boiler technologies - state-of-the-art, ecological evaluation and future developments"

Gerold Thek, Bios Bioenergiesysteme GmbH, Austria

Austrian pellet boiler technologies – state-of-the-art, ecological evaluation and future developments

Dipl.-Ing. Gerold Thek

Prof.Dipl.-Ing.Dr. Ingwald Obernberger

BIOS BIOENERGIESYSTEME GmbH

Inffeldgasse 21b, A-8010 Graz, Austria

TEL.: +43 (316) 481300; FAX: +43 (316) 4813004

E-MAIL: office@bios-bioenergy.at

HOMEPAGE: http://www.bios-bioenergy.at

Introduction

- Austrian pellet market
- Standards for pellet furnaces
- Pellet combustion technology
  - Feeding
  - Storage
  - Burn-back protection
  - Basic burner principles
  - Technical details
    (furnace geometry, materials, control systems, boiler technology, de-ashing)
- Emissions
- Future developments

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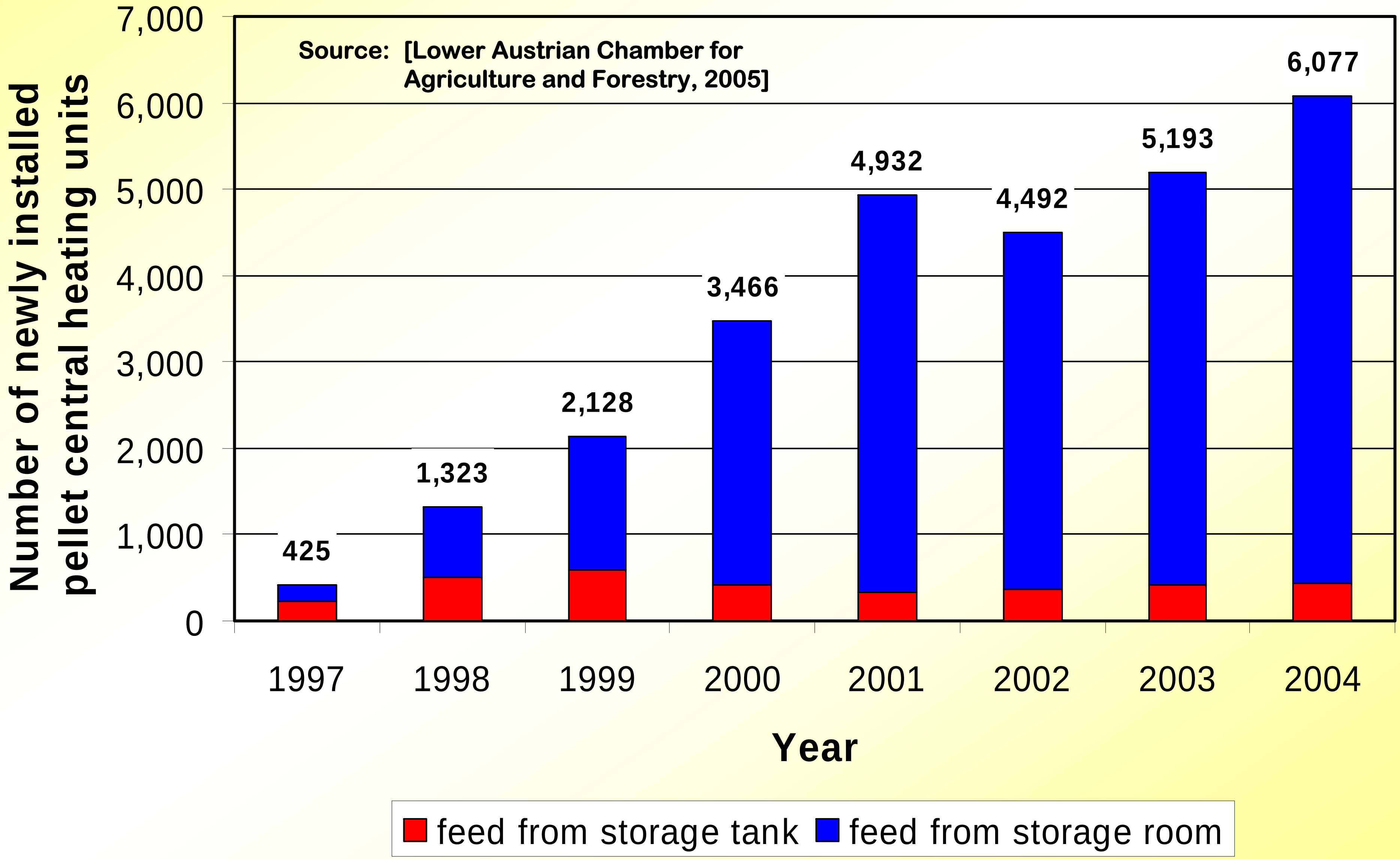
Development of small-scale pellet furnaces in Austria



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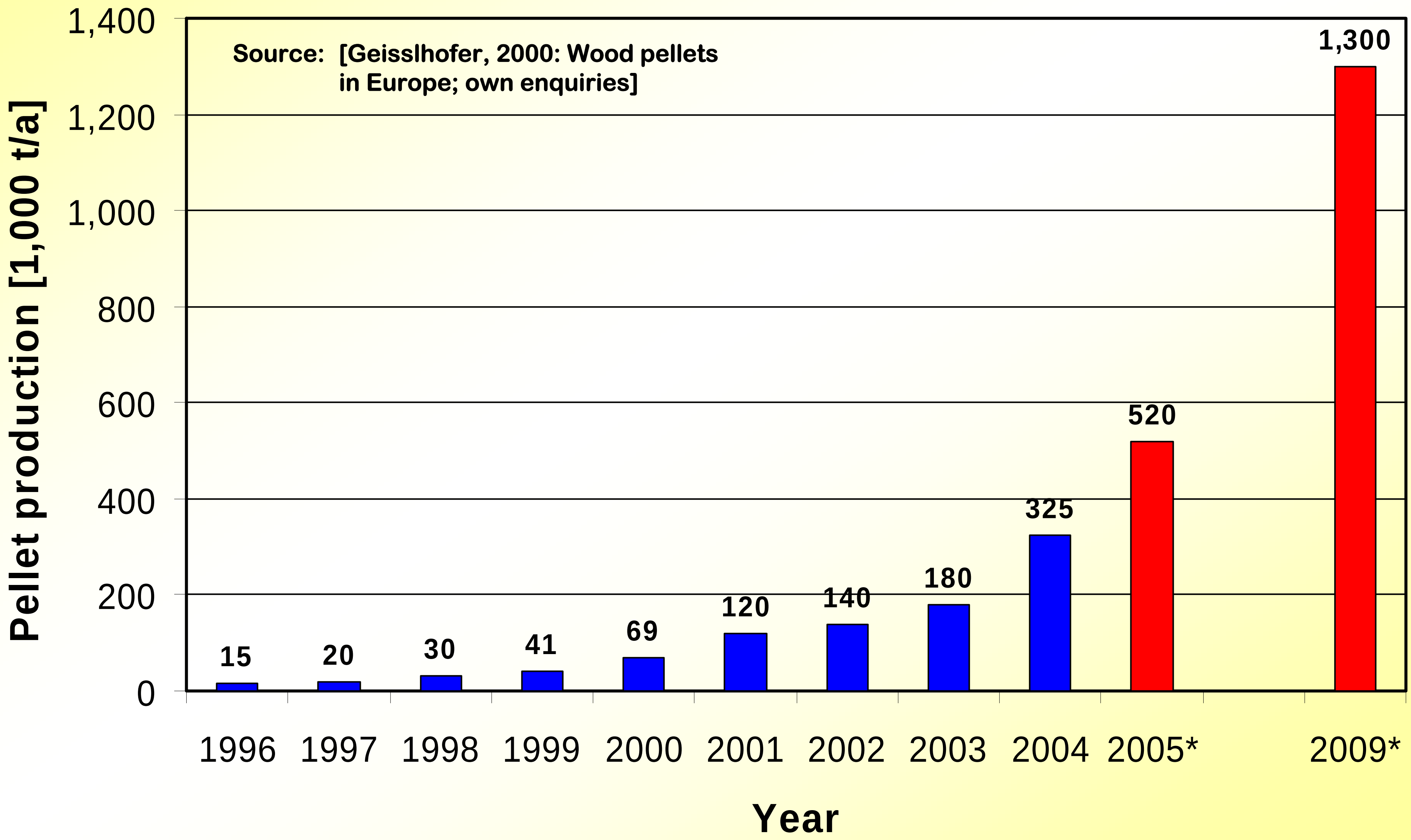
Pellet production in Austria – present state and outlook



* estimate

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Pellet consumption in Austria (year 2004)

- About 28,000 pellet central heating systems already installed in Austria
- Total nominal boiler capacity installed: about 520 MW
- Annual utilisation rate: about 74%
- Boiler full load operation hours: 1,500 h p.a.
- Net calorific value of pellets: 4.9 kWh/kg (w.b.)

➔ Pellet consumption in Austria approximately 216,000 t/a (related to pellet central heating systems)

➔ Additional amounts related to pellet stoves and medium-scale pellet furnaces (100 to 1,000 kW_{th})

➔ Difference to production: mainly export

General framework in Austria

- Investment subsidies granted in Austria on average 25 % (depending on the Austrian provinces)
- Currently 18 pellet producers active or near start-up in Austria
- Pellet quality, transport and storage regulated by ÖNORM M 7135, M 7136 and M 7137
- Quality of pellet furnaces regulated by ÖNORM EN 303-5
- Supply of pellets in Austria assured throughout the country by a well organised distribution network
- About 30 manufacturers of small-scale pellet furnaces in Austria

ÖNORM EN 303-5

parameter	value
valid for heating boilers with a nominal boiler capacity up to	300 kW
testing required by law	yes
all solid fuels (biomass and fossil fuels) are permitted	yes
maximum organic carbon (OGC) emission [mg/MJ_{NCV}]	40
maximum CO emission [mg/MJ_{NCV}]	500
maximum NO_x emissions [mg/MJ_{NCV}]	150
maximum dust emissions [mg/MJ_{NCV}]	60
minimum combustion efficiency	*

*depending on the nominal boiler capacity (see following slide)

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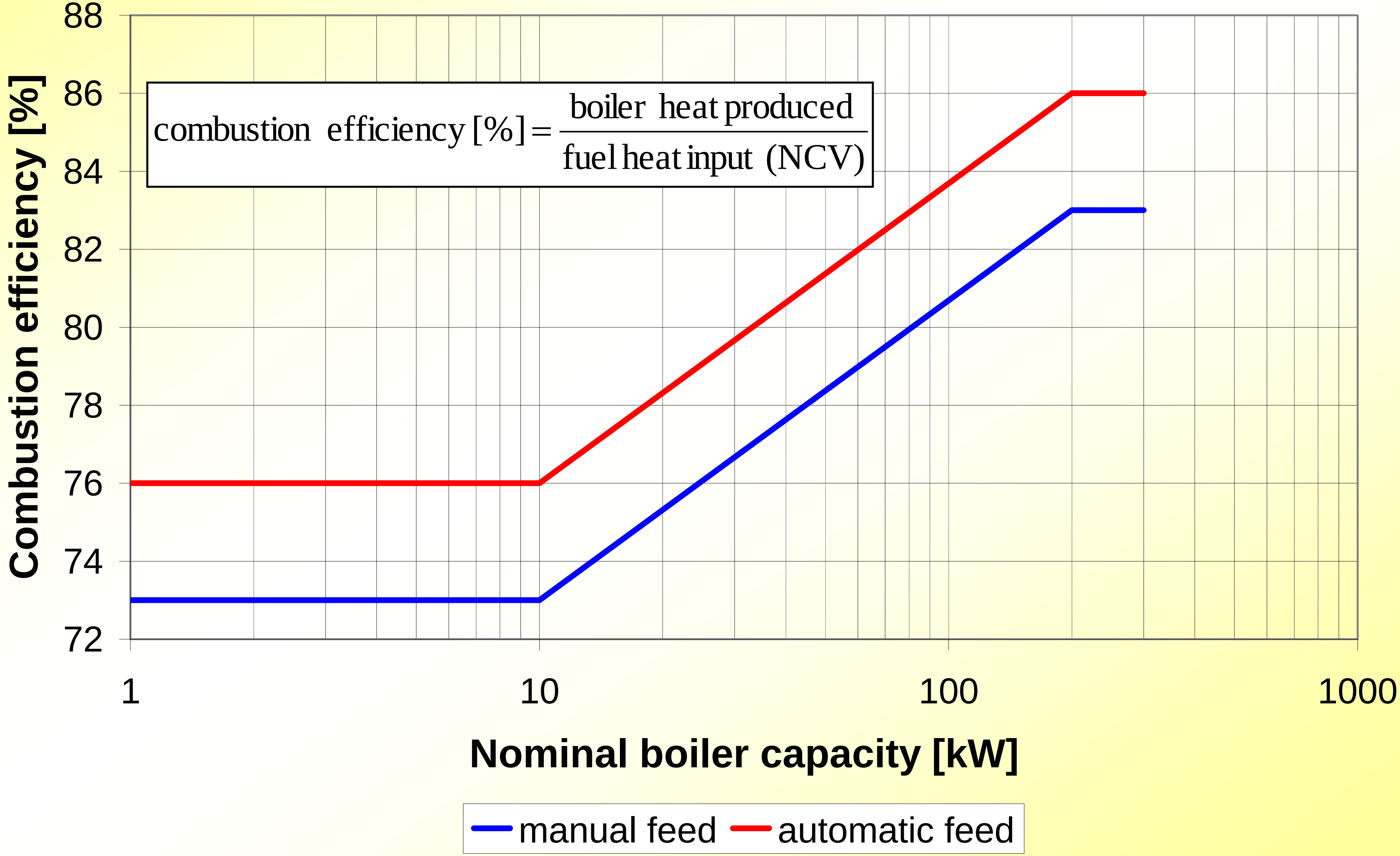
Minimum combustion efficiency according to ÖNORM EN 303-5

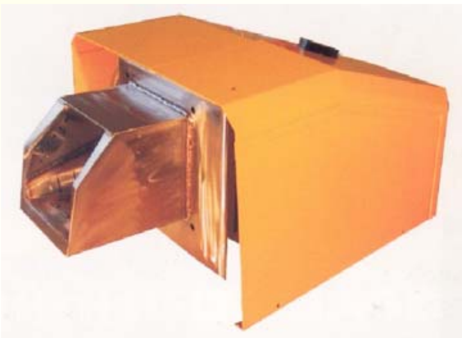


Pellet combustion systems

Pellet stoves

Source: [RIKA Metallwaren-ges.m.b.H. & Co KG, Austria]

Pellet burners



Source: [Gilles Energie und Umwelttechnik GmbH, Austria]

Pellet central heating systems

Source: [GUNTAMATIC Heiztechnik GmbH, Austria]

Grate fired pellet boilers for medium-scale applications (150 to 300 kW_{th})

Source: [KWB Kraft und Wärme aus Biomasse GmbH, Austria]

Feeding and storage systems used

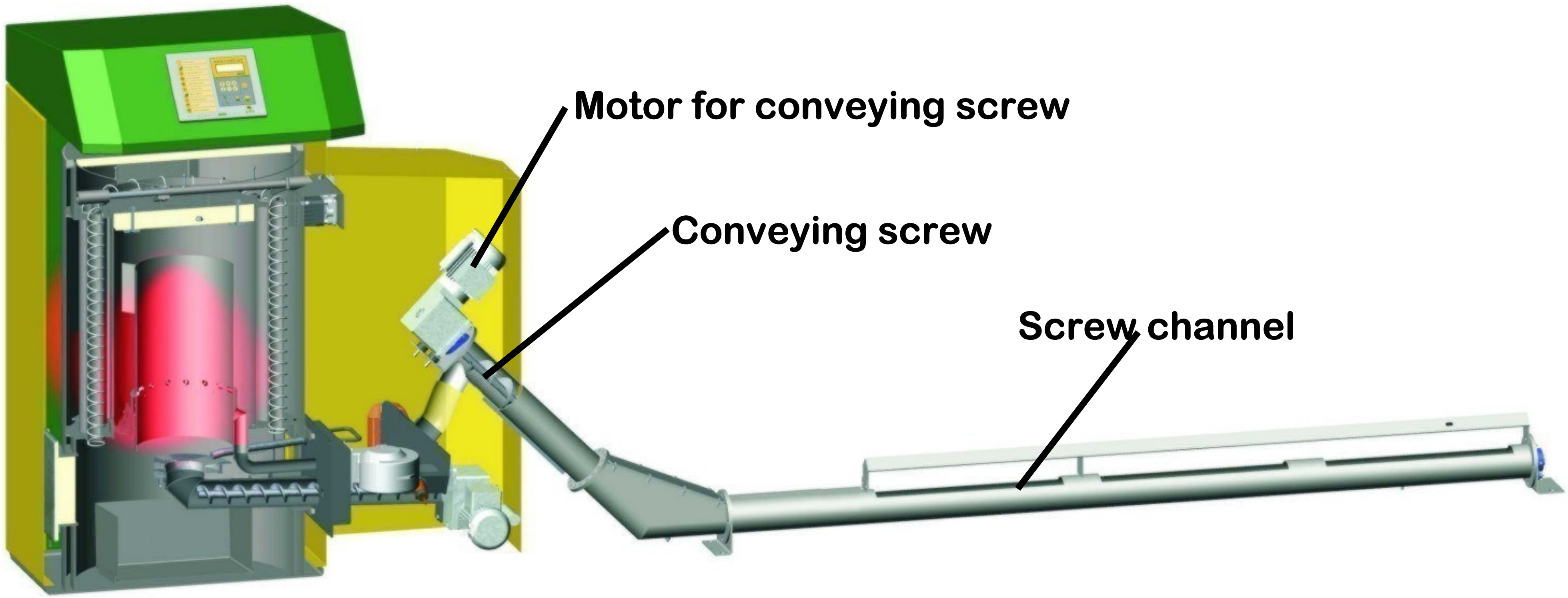
Feeding systems

- Screw conveyor (inflexible)
- Screw conveyor (flexible)
- Pneumatic system
- Pneumatic system / screw conveyor combination
- Agitator / screw conveyor combination

Storage systems

- Storage room (88 %)
- Integrated store (12 %)
- Underground storage tank

Screw conveyor (inflexible)



Source: [KWB – Kraft und Wärme aus Biomasse GmbH, Austria, 2002]

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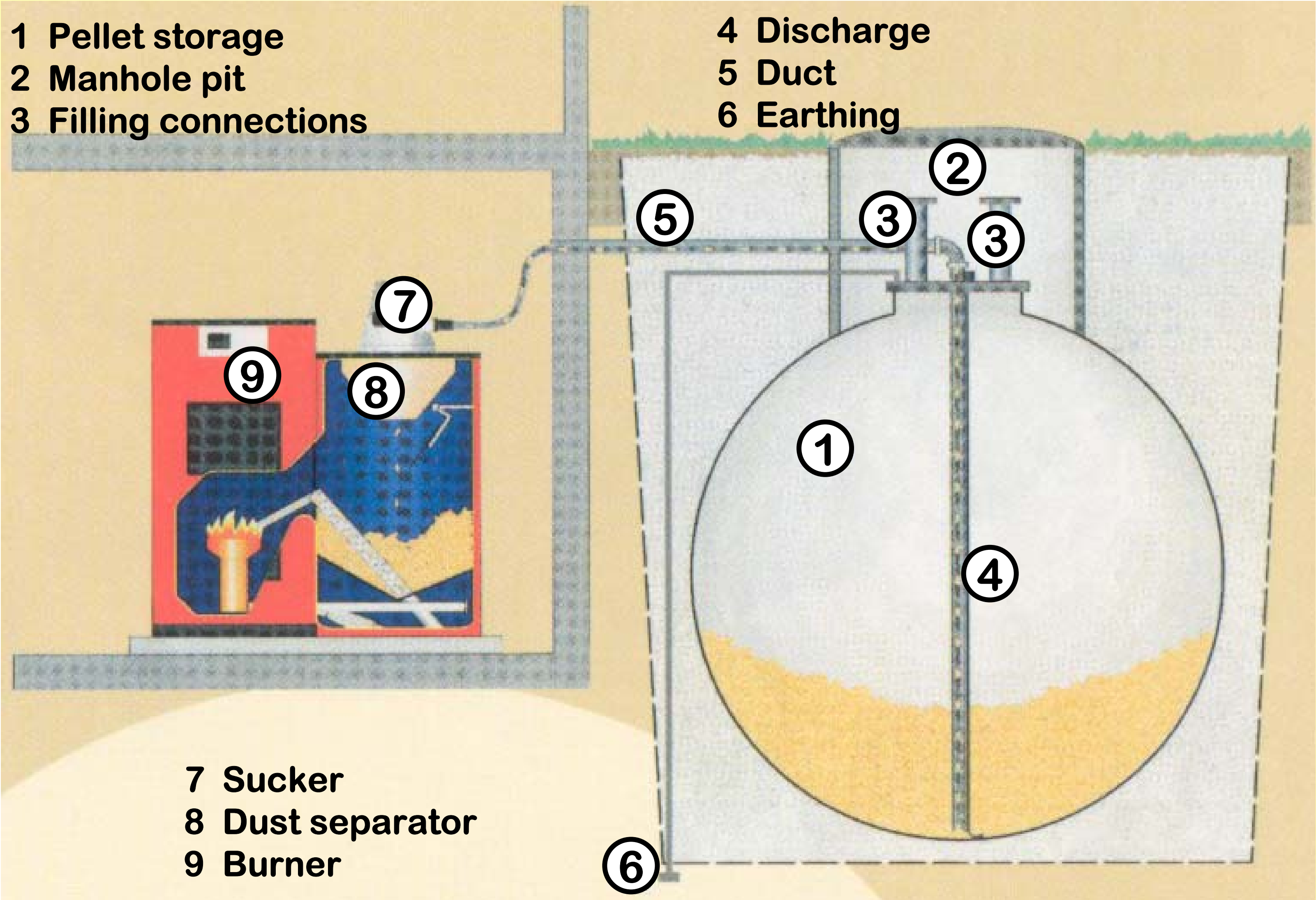
Underground storage tank



Source: [Stefan Nau GmbH & Co. KG, Germany, 2002]

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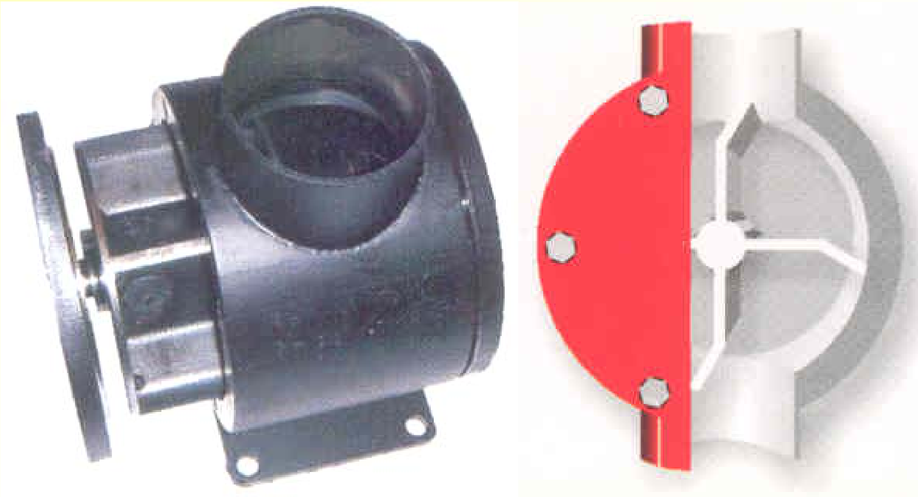
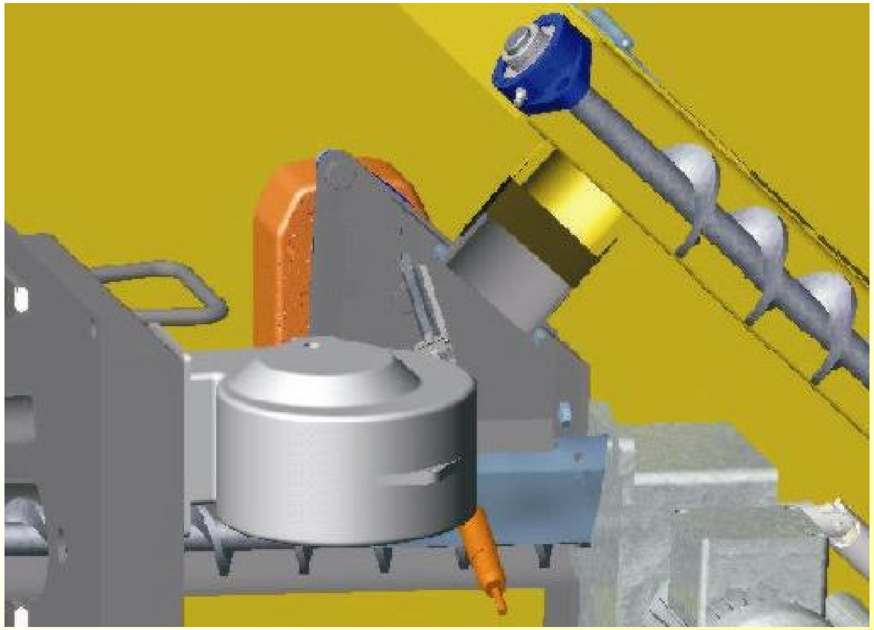
Burn-back protection systems (1)

Cellular wheel sluice



Source: [COMPACT Heiz- und Energie-systeme GesmbH, Austria]

Fireproof valve



Source: [KWB – Kraft und Wärme aus Biomasse GmbH]

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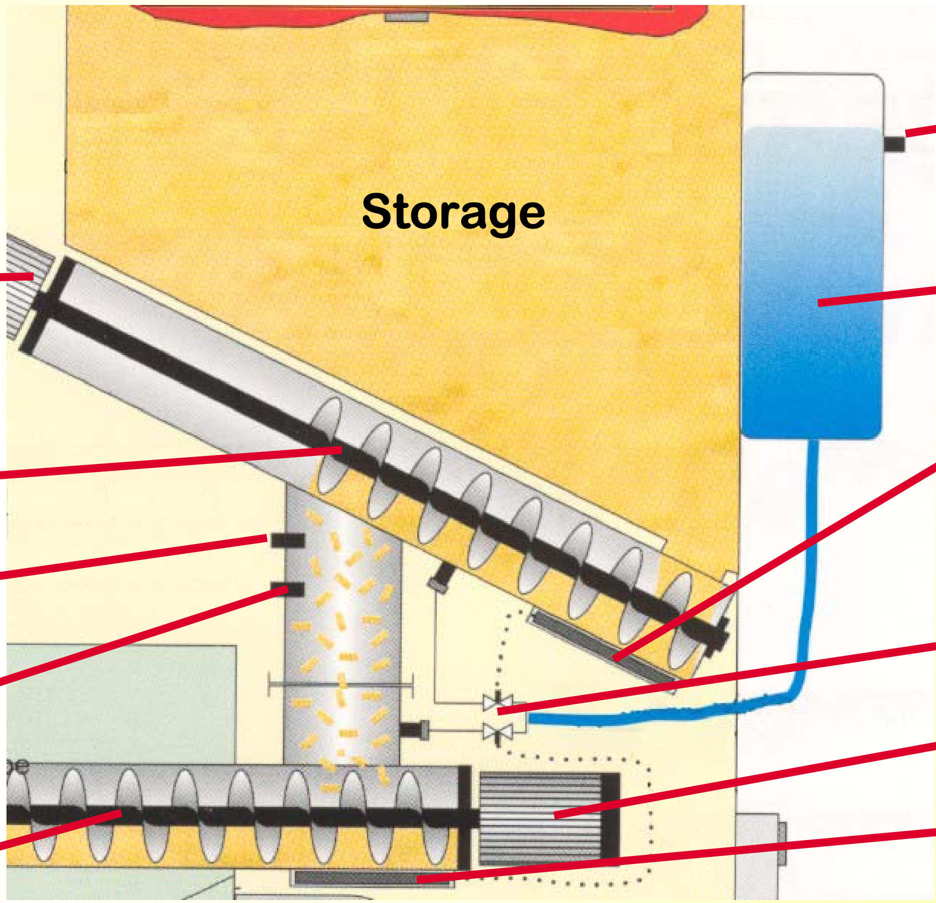
Burn-back protection systems (2)

Extinguisher system



Source: [Anton Eder GmbH, Austria]

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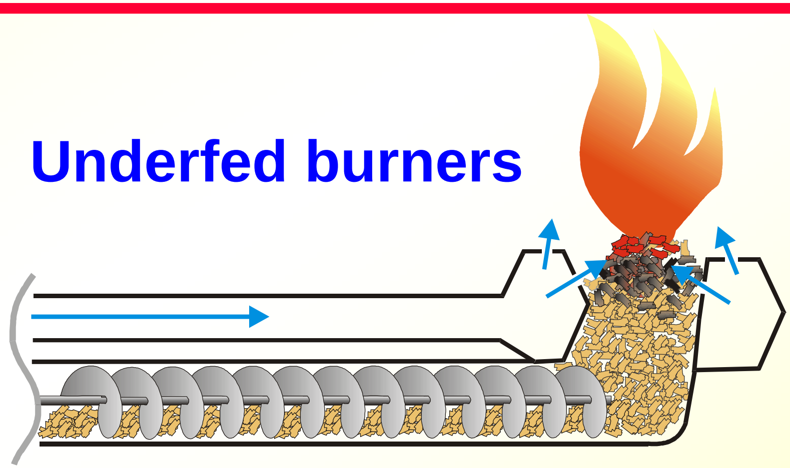
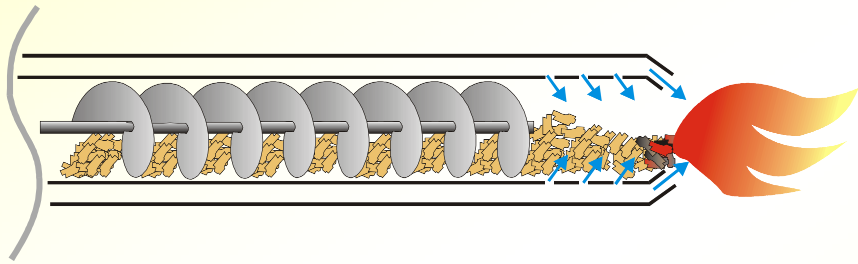
Basic principles of wood pellet burners

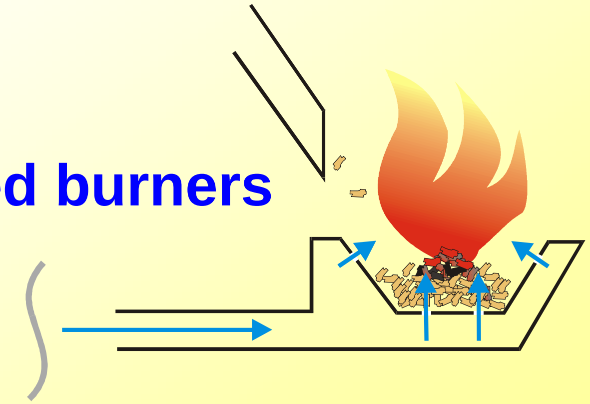
- Underfed burners



- Horizontally fed burners

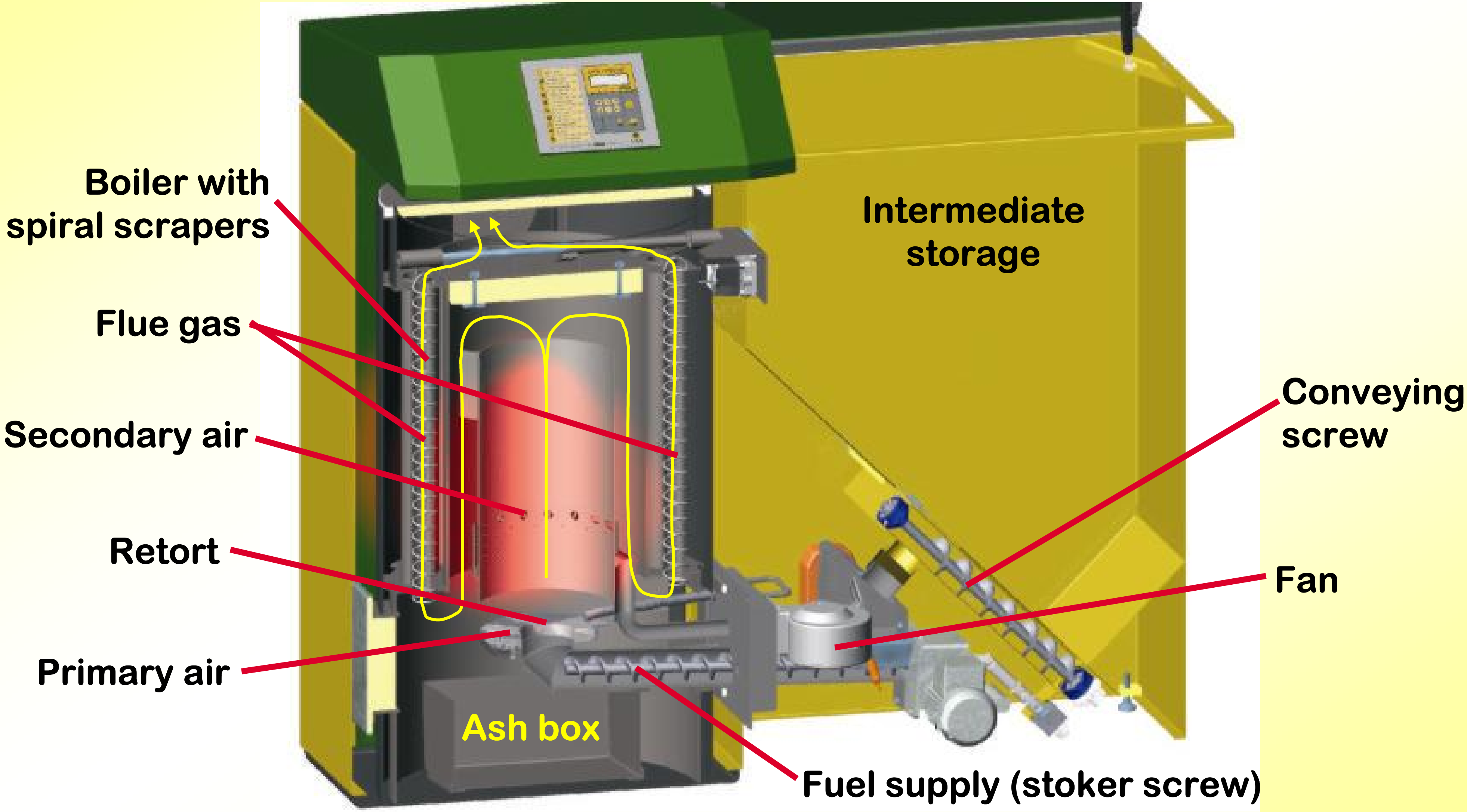


- Overfed burners



Source: [Handbook of Biomass Combustion and Co-Firing, IEA, 2002]

Underfed burner

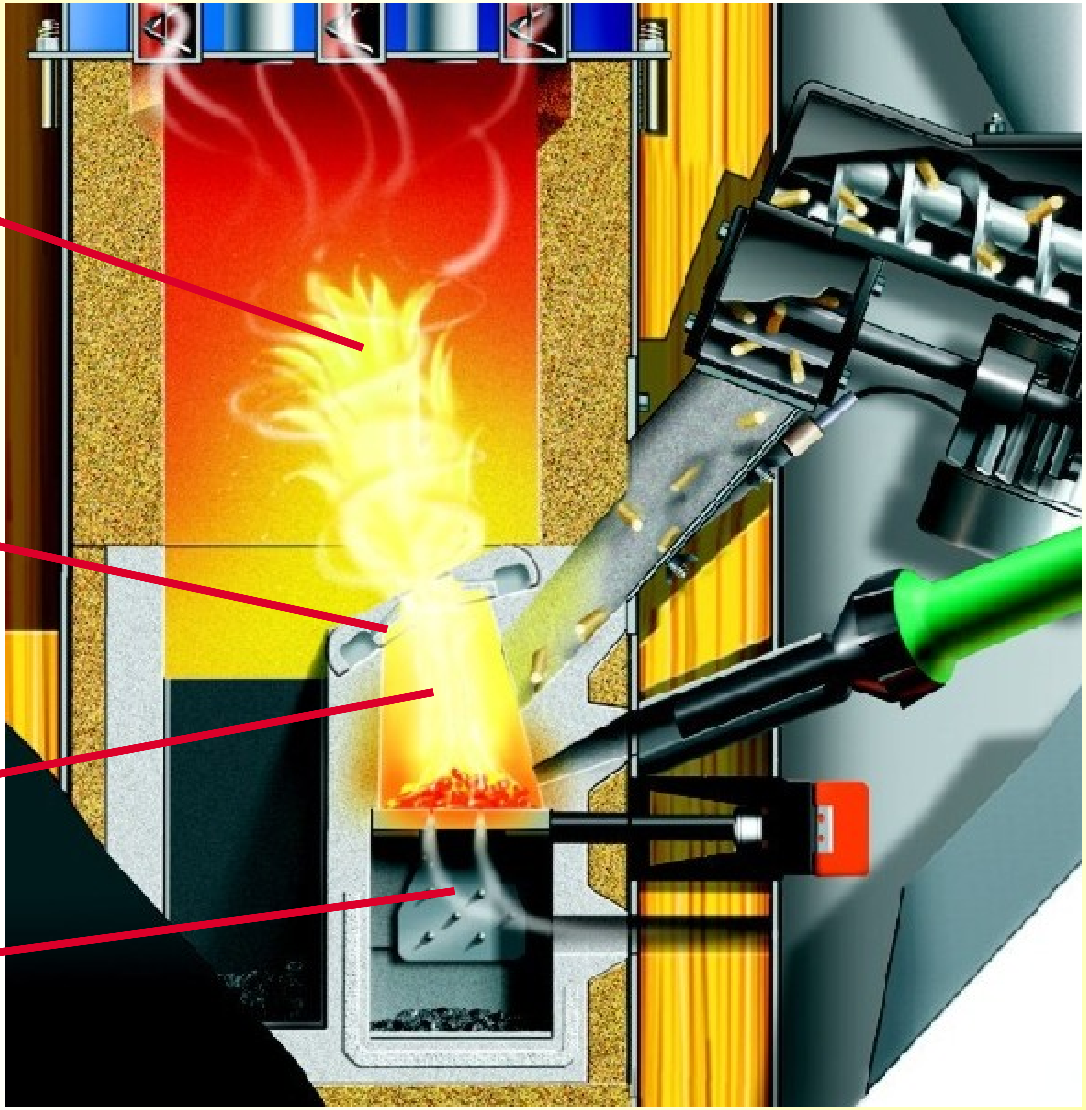


Source: [KWB – Kraft und Wärme aus Biomasse GmbH, Austria, 2002]

Geometry of the combustion chamber – important parameters

- **Air staging**
- **Mixing of secondary air and flue gas**
  (position and design of the secondary air nozzles)
- **Appropriate dimensioning of primary and secondary combustion zone**
  (residence time)
- **Good utilisation of the furnace volume**
  (flow distribution)
- **Even temperature distribution**
  (furnace temperature control)

Air staging and optimised mixing between flue gas and secondary air



Source: [GUNTAMATIC Heiztechnik GmbH, Austria]

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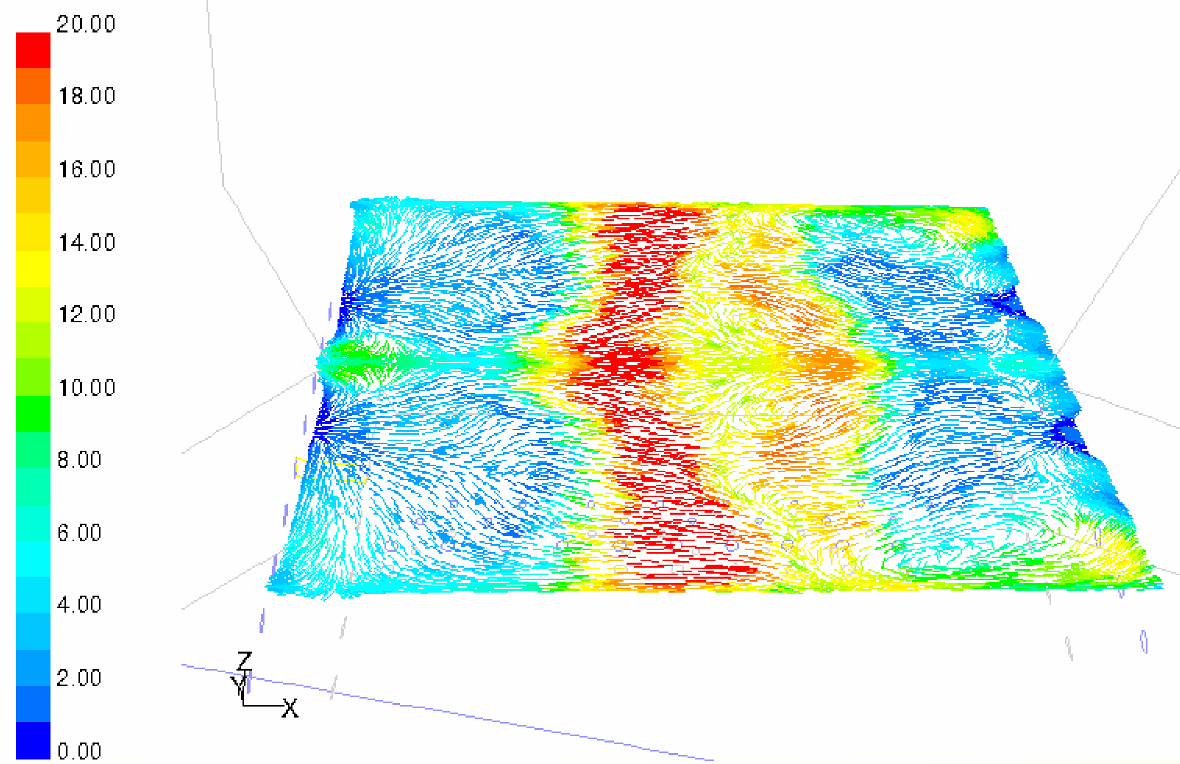
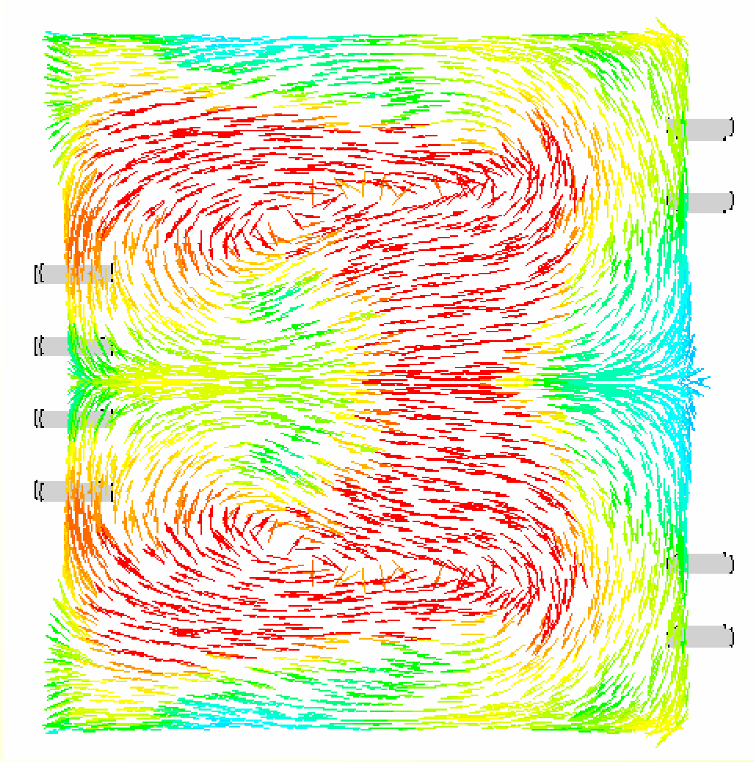
Design and optimisation of the nozzles for the injection of secondary air

**Vectors of the flue gas velocity [m/s]
in the horizontal cross-section right over the secondary air nozzles**



Basic nozzle design



Improved nozzle design

➔ **CFD-based furnace and nozzle design of great relevance**

Source: [BIOS BIOENERGIESYSTEME GmbH, Austria, 2002]

Control systems

Load control

- **Guiding value:** feed water temperature
- **Variables:** fuel and primary air feed

Combustion control

- **Guiding value:** O_2, CO or O_2 and CO concentration in the flue gas (lambda, CO or CO/lambda control)
- **Variable:** secondary air supply

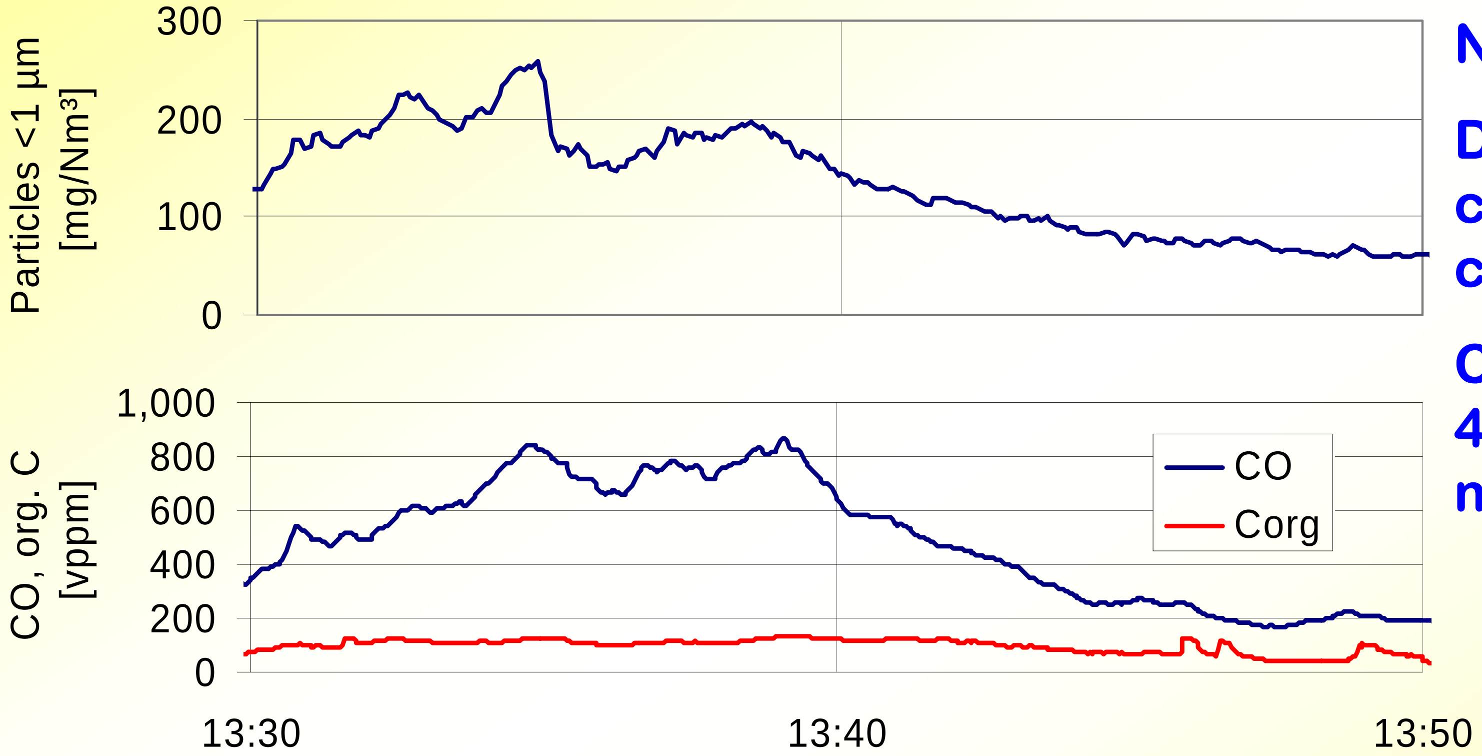
Temperature control

- **Guiding value:** temperature in the combustion chamber
- **Variables:** flue gas recirculation or water-cooled furnace walls

Pressure control

- **Guiding value:** pressure in the combustion chamber
- **Variable:** induced draught fan (frequency)

Relevance of automatic control systems



Notes:

Data related to the current operating conditions

Change of load from 40% part load to nominal load

- **Importance of automatic control systems to guarantee low CO, TOC and particulate emissions at all load conditions (start-up, shut-down, load changes, full and part load operation)**

Geometry

- Usually vertical fire tube boilers (one or three-pass boilers)

Boiler cleaning

- Fully automatic by spiral scrapers in the fire tubes
- Semi-automatic by spiral scrapers in the fire tubes with a lever from the outside
- Manually

Automatic boiler cleaning systems increase the efficiency and reduce dust emissions

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Fully automatic boiler cleaning system

Source: [BIOS BIOENERGIESYSTEME GmbH, Austria, 2002; furnace of KWB - Kraft und Wärme aus Biomasse GmbH]

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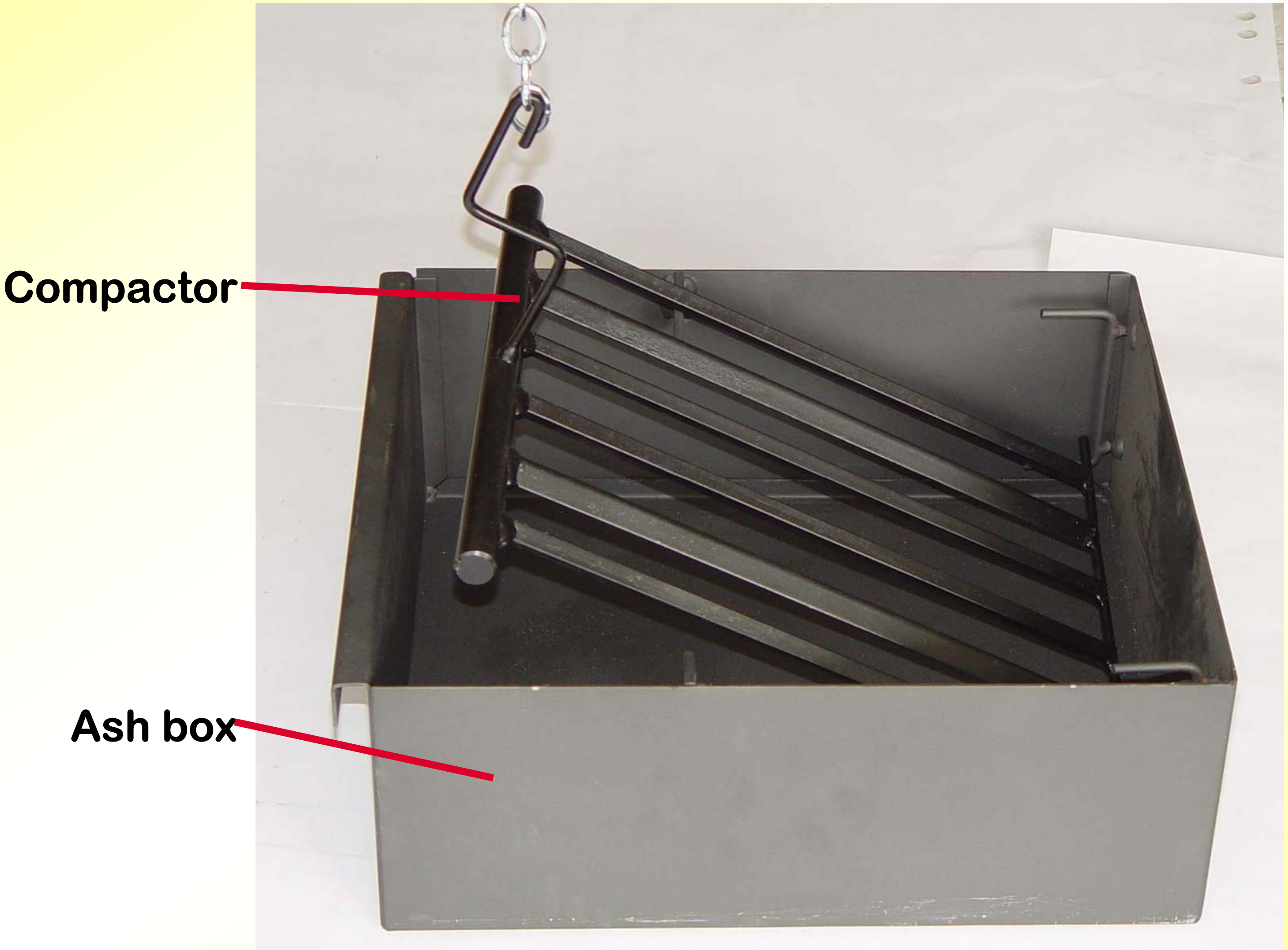
De-ashing systems

- Usually ash collection in an ash box
  → ash box must be emptied periodically

- Ash compaction systems partly applied
  → ash box must be emptied periodically in longer periods of time

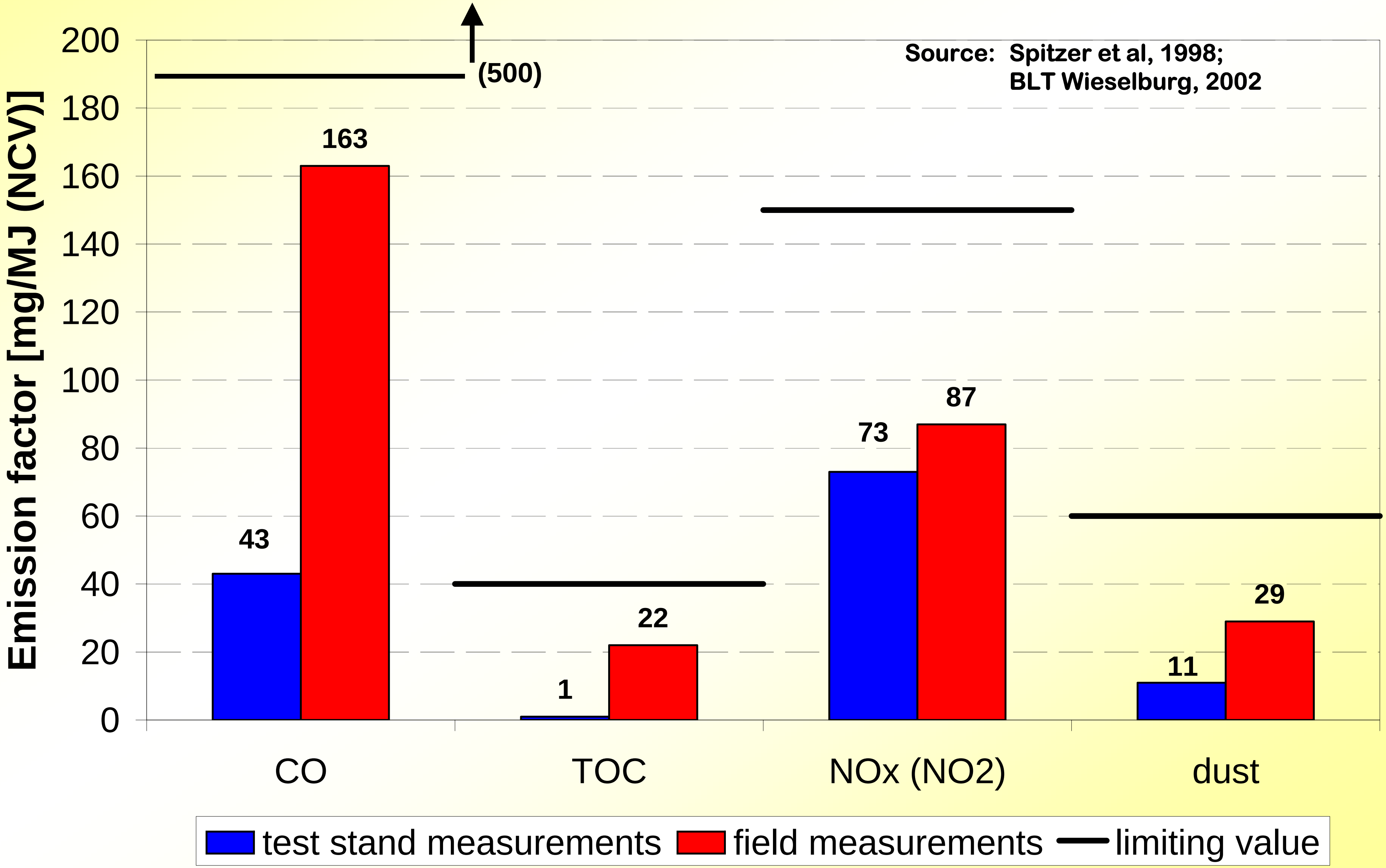
- Fully automatic de-ashing system by a screw conveyor in an external container
  → ash box must be emptied only about once a year

Ash compaction system



Source: [KWB – Kraft und Wärme aus Biomasse GmbH, Austria, 2002]

Emissions


Emission factor [mg/MJ (NCV)]
200
180
160
140
120
100
80
60
40
20
0
(500)
Source: Spitzer et al, 1998;
BLT Wieselburg, 2002
163
43
1
22
73
87
11
29
CO
TOC
NOx (NO2)
dust
test stand measurements
field measurements
limiting value

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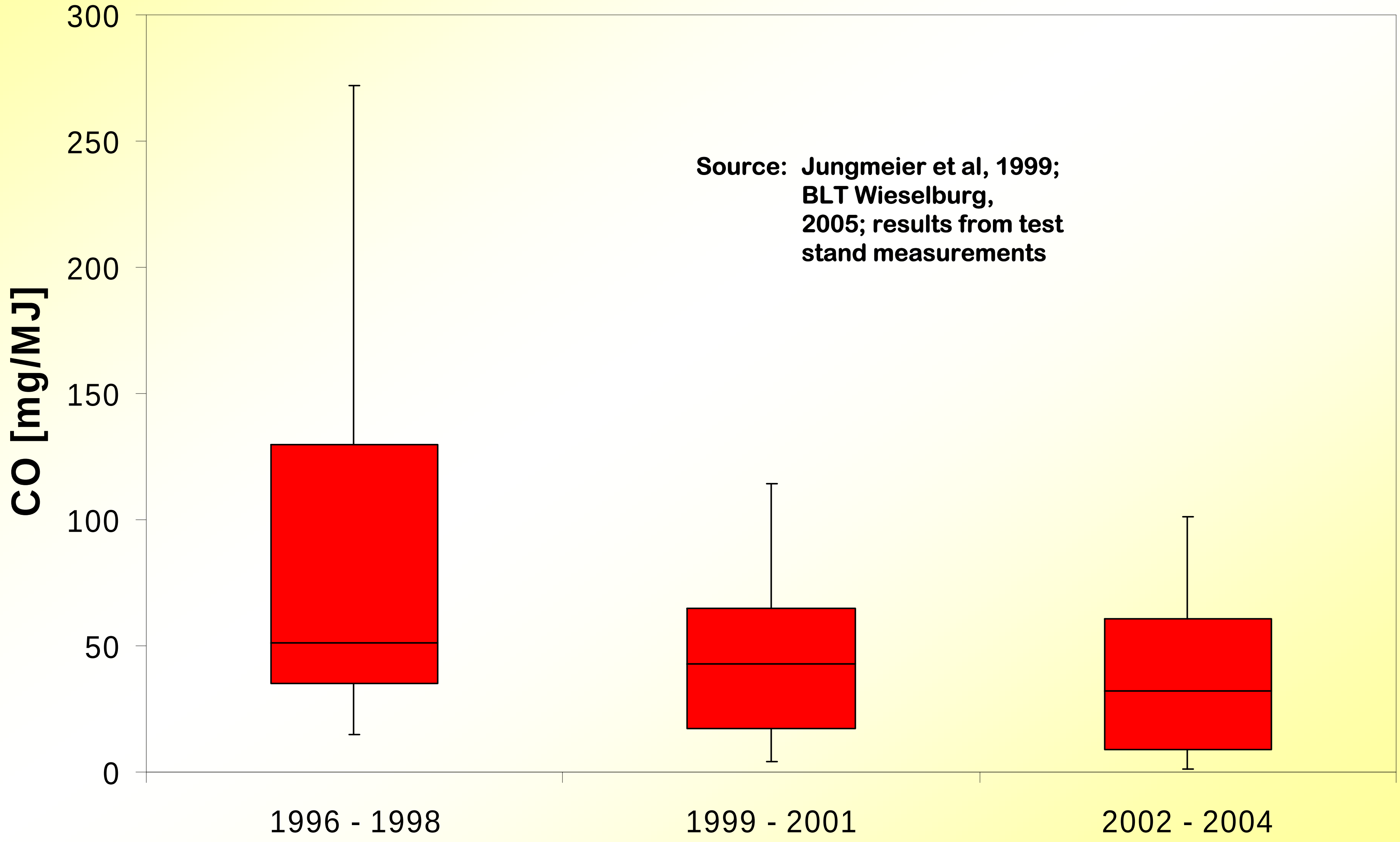
CO emissions – comparison between old and new pellet furnaces



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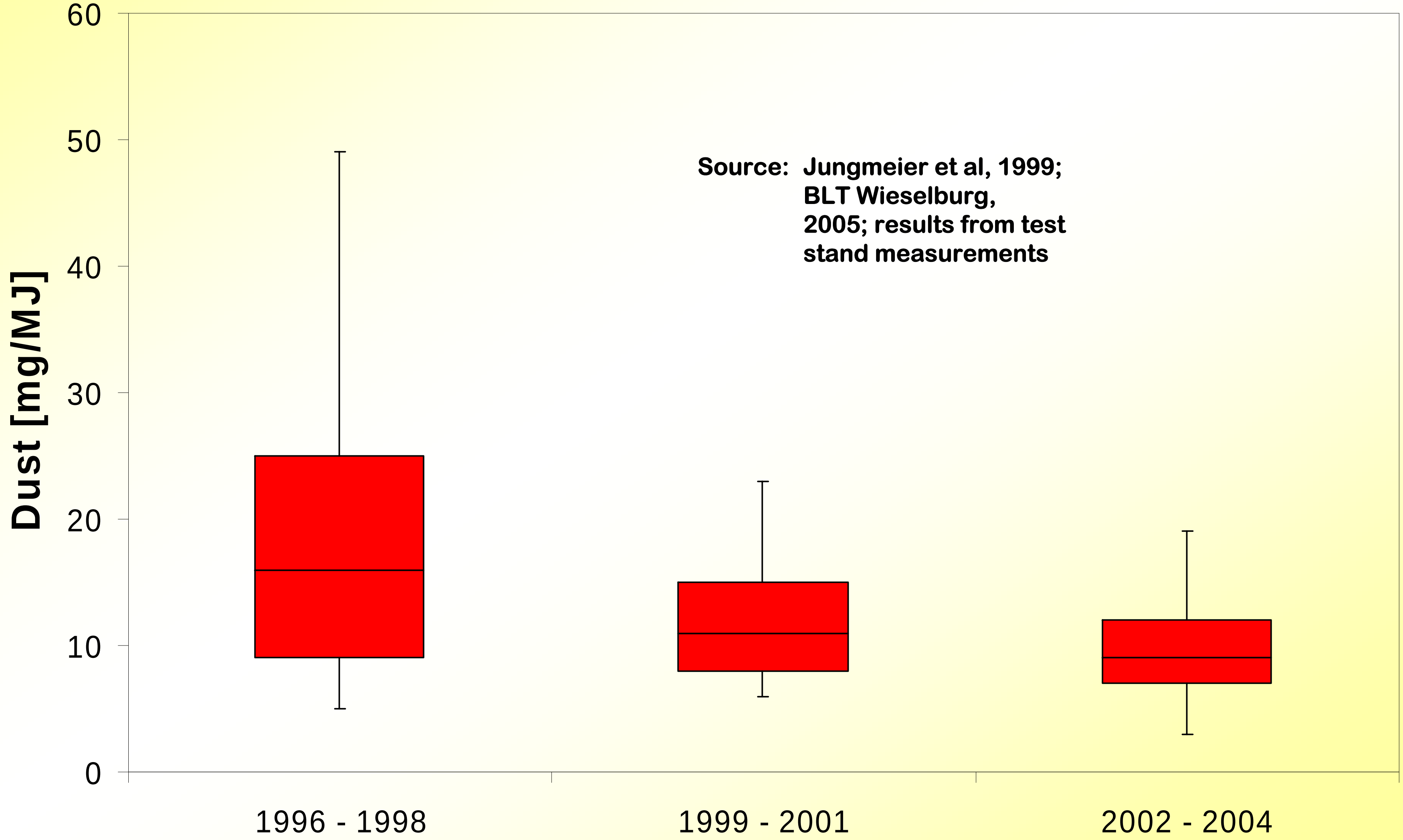
Dust emissions – comparison between old and new pellet furnaces



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Fine particulate emissions – new pellet furnaces

- **About 90 to 95% of the total dust emissions are fine particles (< 1 µm)**
- **Fine particulate emissions from modern pellet furnaces usually have a mass mean diameter of about 0.15 µm**
- **If combustion is complete about 1.5×10^7 particles per cm^3 are formed**
- **A complete burnout of the flue gas is very important to minimise fine particulate emissions**
- **The chemical composition of the fuel strongly influences fine particulate emissions**

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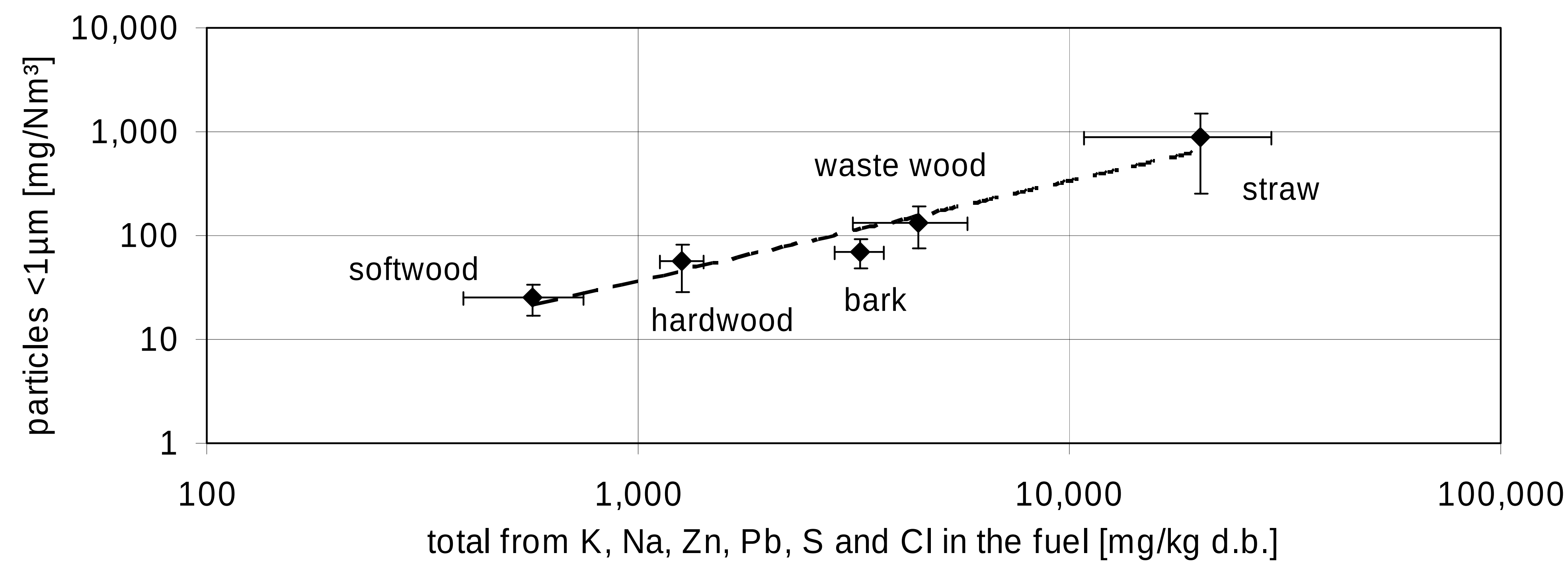
Fine particulate emissions – influence of the fuel composition

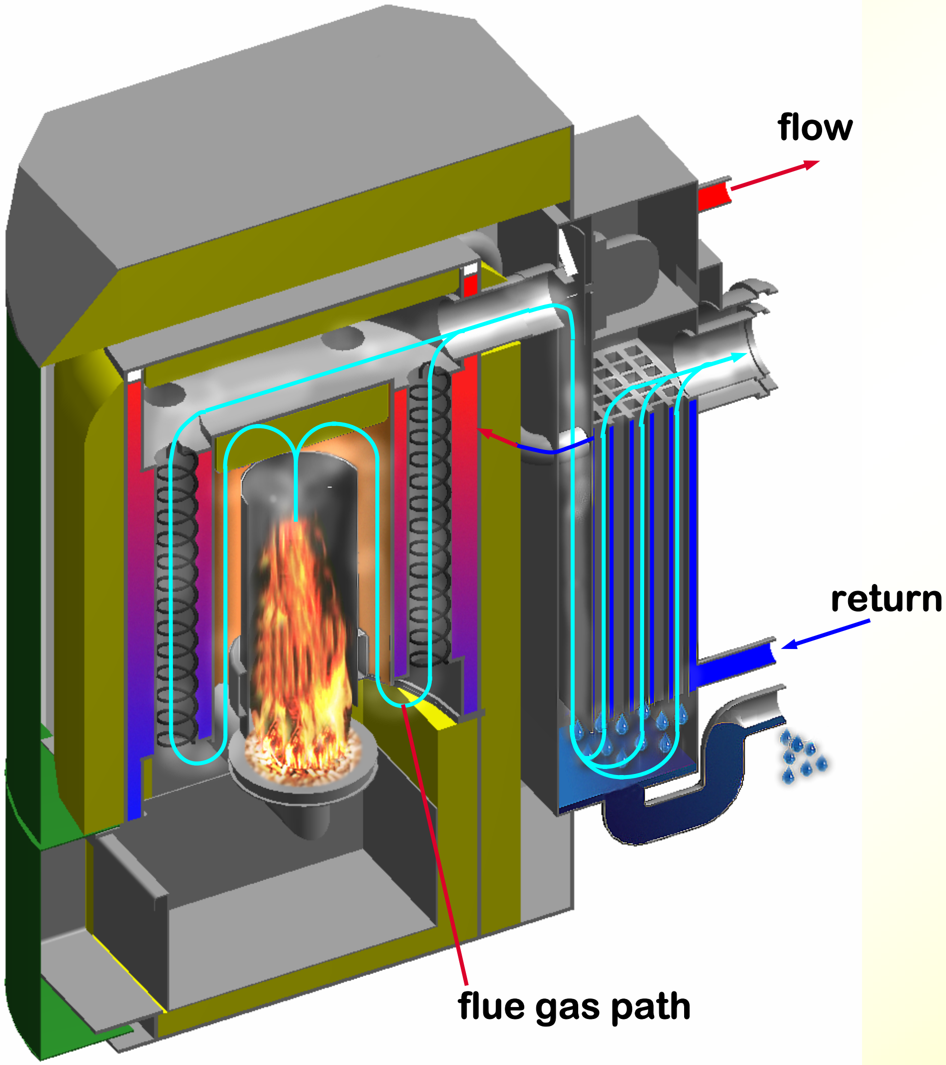


Explanations: Emissions related to dry flue gas and 13 vol.% O_2; d.b. ... dry basis; results from measurements at grate furnaces with nominal capacities between 400 kW_{th} and 50 MW_{th}

Future developments

- **CFD-aided furnace development and optimisation**
- **Medium-scale combustion systems**
  (nominal boiler capacities between 100 and 1,000 kW_{th})
- **Reduction of particulate emissions (especially PM1)**
- **Small-scale dust burners**
  (utilisation of pulverised pellets)
- **Utilisation of herbaceous / non-woody biomass fuels**
- **Combination of pellets with solar systems**
- **Pellet furnaces with flue gas condensation**
- **Small-scale CHP systems**
  (e.g. Stirling engines)

Pellet furnace with flue gas condensation



Source: [OkoFEN, Austria, 2004]

- First pellet boiler with flue gas condensation
- Market introduction: 2004
- Efficiency: 103% (according to type test by BLT Wieselburg)
- Nominal capacities: 8, 10, 15 and 20 kW

BIOENERGIESYSTEME GmbH
Inffeldgasse 21b, A-8010 Graz

New small-scale CHP technology based on Stirling engines for wood chip and pellet furnaces

- **2 pilot plants in operation**
  35 kW_{el} and 70 kW_{el}
- **Start-up:**
  End of 2002 (35 kW_{el}) and
  End of 2003 (70 kW_{el})
- **Operating hours:**
  > 12,000 (35 kW_{el})
  > 4,000 (70 kW_{el})
- **Electric plant efficiency :**
  approximately 11 to 12%
- **Fuels:**
  Pellets, wood chips, sawdust
- **First small series production**
  (7 plants with 35 kW_{el})
- **Comprehensive field tests ongoing**
  (2005/06)

Source: [BIOS BIOENERGIESYSTEME GmbH; MAWERA Holzfeuerungsanlagen GesmbH, Austria, 2005]

Summary

- Rapidly expanding pellet market in Austria
- Several actors, quality standards and subsidies supporting this development
- Proven feeding and combustion technologies available from many furnace manufacturers which ensure a fully automatic operation
- Low emissions with a decreasing tendency for new furnaces
- Several research activities and promising developments focusing on new fields of application, new biomass fuels and emission reduction

Annex 3. Assessment of factors affecting hazardous emissions from residential wood-burning appliances

Fernando Preto; CANMET Energy Technology Centre – Ottawa, Canada

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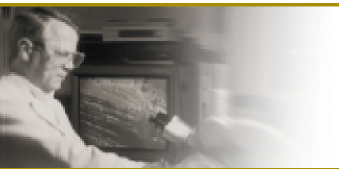
CLEAN ENERGY TECHNOLOGIES

Fernando Preto

EMISSIONS FROM RESIDENTIAL WOOD COMBUSTION

IEA Task 32 Workshop
Recent Developments in Small Scale Combustion Devices
Paris, October 21, 2005

Canada



Objectives

To study hazardous emissions from residential wood combustion devices in order to to provide information for reducing the amount of particulates, VOCs and dioxins and furans and update database of the current contribution of residential appliances to Canadian air sheds

Hazardous Substances Evaluated:

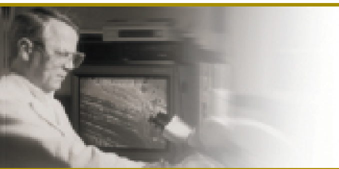
- Particulate Matter
- Volatile Organic Compounds
- Dioxins and Furans

Background

Residential wood combustion currently accounts for 15% of biomass energy use in Canada (0.9 % of Canada's primary energy use)

Environment Canada has estimated that 14% of total national $PM_{2.5}$ emissions from anthropogenic sources (excluding forest fires) are from residential combustion systems

Environment Canada has estimated that 15% of total national VOC emissions are from residential combustion systems



Emissions Requirements

- The United States has national emissions requirements, and these apply only to a limited range of appliances, generally those which would be considered to be wood stoves. U.S. emission limits are 7.5 g/h for non-catalytic appliances and 4.1 g/h for catalyst equipped appliances. These figures compare to typical emissions of approximately 20 - 30 g/h for pre-regulation appliances.
- In Canada, the province of British Columbia has adopted the U.S. requirements. In the rest of Canada there are currently no requirements for wood burning appliances to meet any emissions criteria
- Environment Canada, the federal department responsible for such regulation, has initiated the process necessary for adoption of a national regulation
- Canada does have an emissions and efficiency test protocol but it has yet to be mandated by the regulatory authorities.

Canadian Standards

The principal Canadian standards dealing with wood heat systems are summarized below.

- ULC S627 (Cdn), UL1482 (U.S.): Wood and pellet stove safety testing. This standard sets minimum requirements for the construction and clearances to combustibles of wood stoves, including pellet-fired appliances.
- ULC S628 (Cdn), UL737 (U.S.) Similar to S627 but covering inserts.
- CSA B365(Cdn): Sets out installation requirements of wood burning appliances, including uncertified equipment.
- CSA B366.1 (Cdn), UL 391 (U.S.): Requirements similar to S627 for central wood burning systems.
- CSA B415.1 (Cdn), EPA Part 40 (U.S.): Test methods for determination of efficiency and particulate emissions from wood-fired appliances, including conventional and pellet stoves, inserts, central furnaces and boilers, small commercial systems, and “high performance” fireplaces. Maximum particulate emission levels are specified. An ASTM document is also being developed to provide testing requirements for outdoor boilers (WK 5982).

Experimental Program

- Appliance type:
  - Level 1: conventional “old” cordwood (FMB)
  - Level 2: conventional “new” cordwood (CTS)
  - Level 3: certified cordwood (RCY)
  - pellet stove (DPP)
- Burn rate:
  - Low: 1.5 kg/hr cordwood
  - High: 3.0 kg/hr cordwood
- Fuel:
  - hardwood - red oak; moisture 15% and 35%
  - Softwood – pine; moisture 15% and 35%

Level 1 Appliance (FMB)

- "box with a hole in the back"
- partial sidewall refractory lining only

Canada

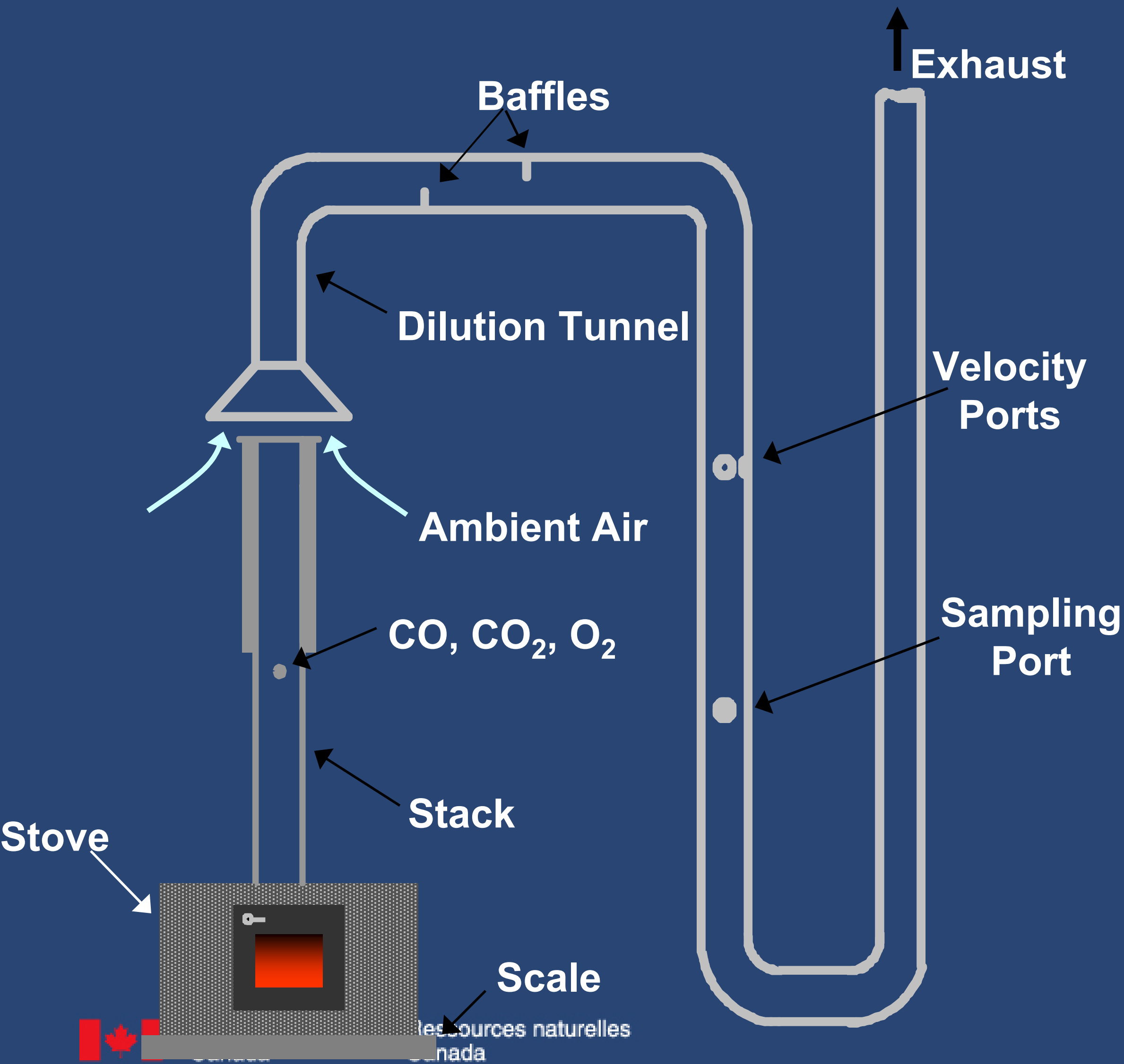
Level 2 Appliance (CTS)

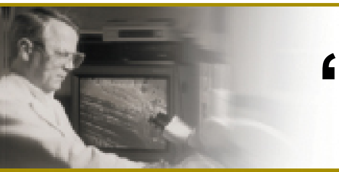
- current "conventional" design
- baffle at back near exit
- partial refractory lining

Level 3 Appliance (RCY)

- USEPA Certified Stove
- Full refractory
- Refractory baffle
- Air staging

Sampling Set-up





“Real Life” Experimental Procedure

1. Small fire started with newspaper & kindling
2. Pre-test charge loaded & desired air rate set
3. Pre-test charge burnt until 20-25% remained
4. Start: test charge loaded & PM sampling started
5. End: test charge consumed & sampling stopped

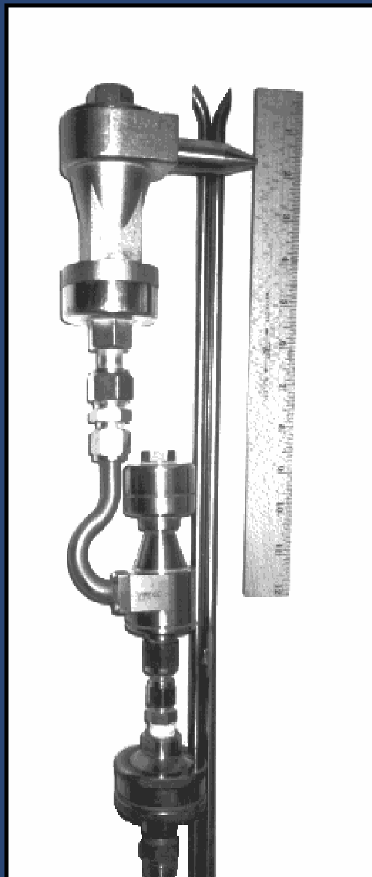
All of the cordwood was split and the bark was intact. As fuel size can affect emission rates, it was kept as constant as possible. The cross-section of the fuel pieces ranged between 65 and 130 cm2 and the length was 40 cm.

Canadian Standards Association
Technical Standard B415.1 Performance Testing
of Solid-Fuel-Burning Appliances

Particulate Sampling

Particulate Sampling:

- sampling head disassembled
- filter placed in dessicator
- cyclones brushed & rinsed with acetone, rinses transferred to 3 beakers (>10µm, <10 µm & >2.5 µm, <2.5 µm)
- acetone evaporated, beakers placed in dessicator
- mass of each size fraction determined gravimetrically



Combined Cyclone Sampling Head

VOC Sampling

VOC Sampling:

– Collected using Method 30 – VOST which measures 35 VOCs
– Replace Tenax cartridge pairs after 40 minutes to ensure VOC capture

Volatile Organic Compound (VOC)

- Any carbon containing compound which participates in atmospheric photochemical reactions
- Most commonly Includes:

  Acetone; Acrylonitrile; Benzene; Carbon disulfide; Carbon tetrachloride; Chlorobenzene; Chloroethane; Chloroform; Chloromethane; Ethylbenzene; Iodomethane; Methylene chloride; Styrene; Toluene; Vinyl chloride; Xylenes.

  Bromodichloromethane; Bromoform; Bromomethane; Chlorodibromomethane; Dibromomethane;

  1,1-Dichloroethane; 1,2-Dichloroethane; 1,1-Dichloroethene X; trans-1,2-Dichloroethene; 1,2-Dichloropropane; cis-1,3-Dichloropropene; trans-1,3-Dichloropropene;; 1,1,2,2-Tetrachloroethane; Tetrachloroethene; 1,1,1-Trichloroethane; 1,1,2-Trichloroethane; Trichloroethene; Trichlorofluoromethane; 1,2,3-Trichloropropane.
- Excludes carbon monoxide, carbon dioxide, methane, ethane, metallic carbides or carbonates, ammonium carbonate and carbonic acid

VOC Results

- Cordwood Stove VOC emissions range:
  - **38 mg/kg fuel**
    (certified, hardwood, low moisture, high burn rate)
  - **13,097 mg/kg fuel**
    ("old" stove, softwood, high moisture, low burn rate)

- VOC Species
  - **most species were "Non-Detect"**
  - **samples contained primarily BTEX**
    (benzene, toluene, ethylbenzene, xylene)
    & styrene

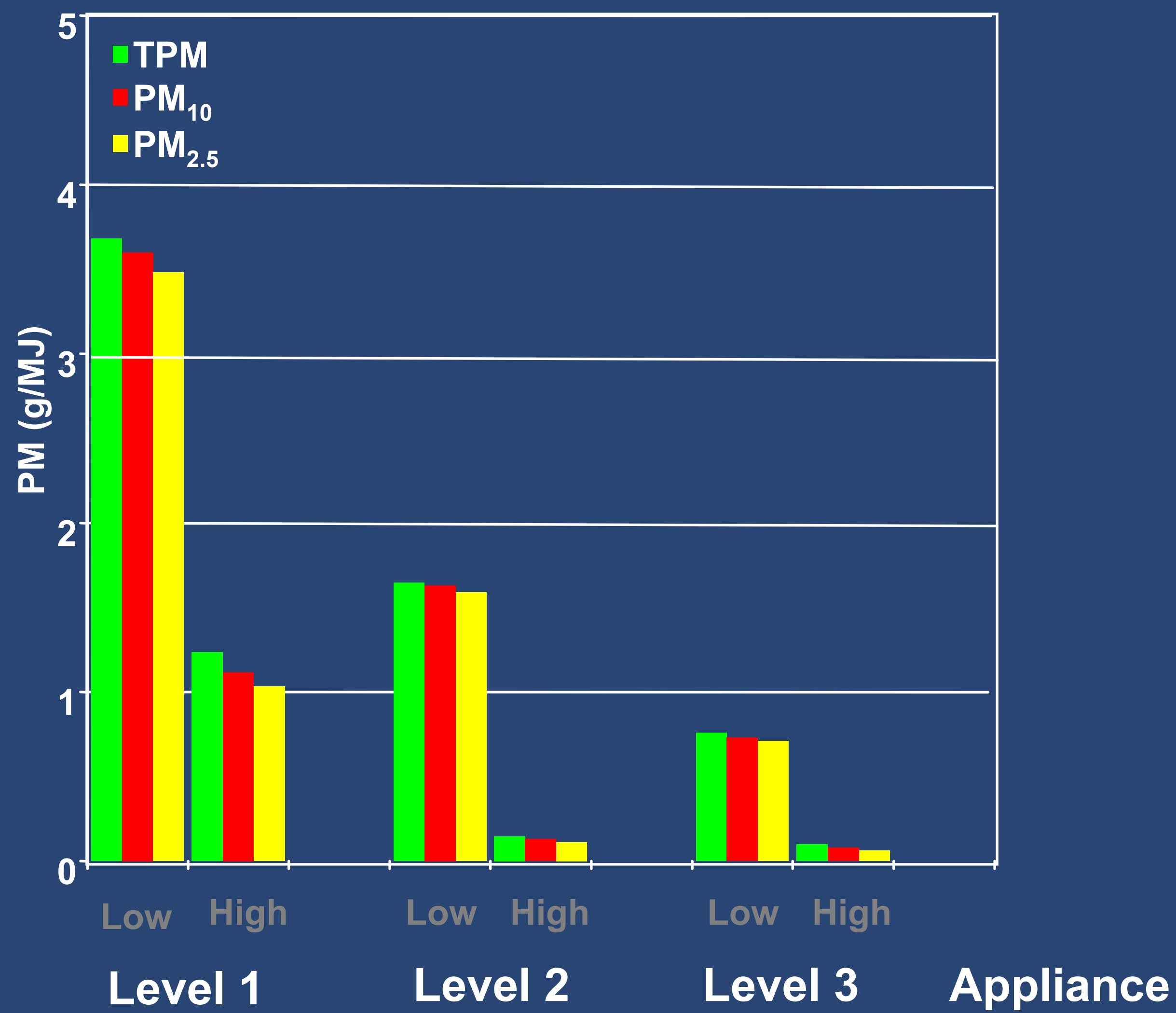
Particulate Matter Results

Total PM emissions ranged from 0.019 g/MJ for the pellet stove operated at a high burn rate to 3.68 g/MJ for the “old” conventional stove operated at a low burn rate. Average emissions are 1.68 g/MJ for the conventional cordwood stove and 0.44 g/MJ for certified non-catalytic stoves.

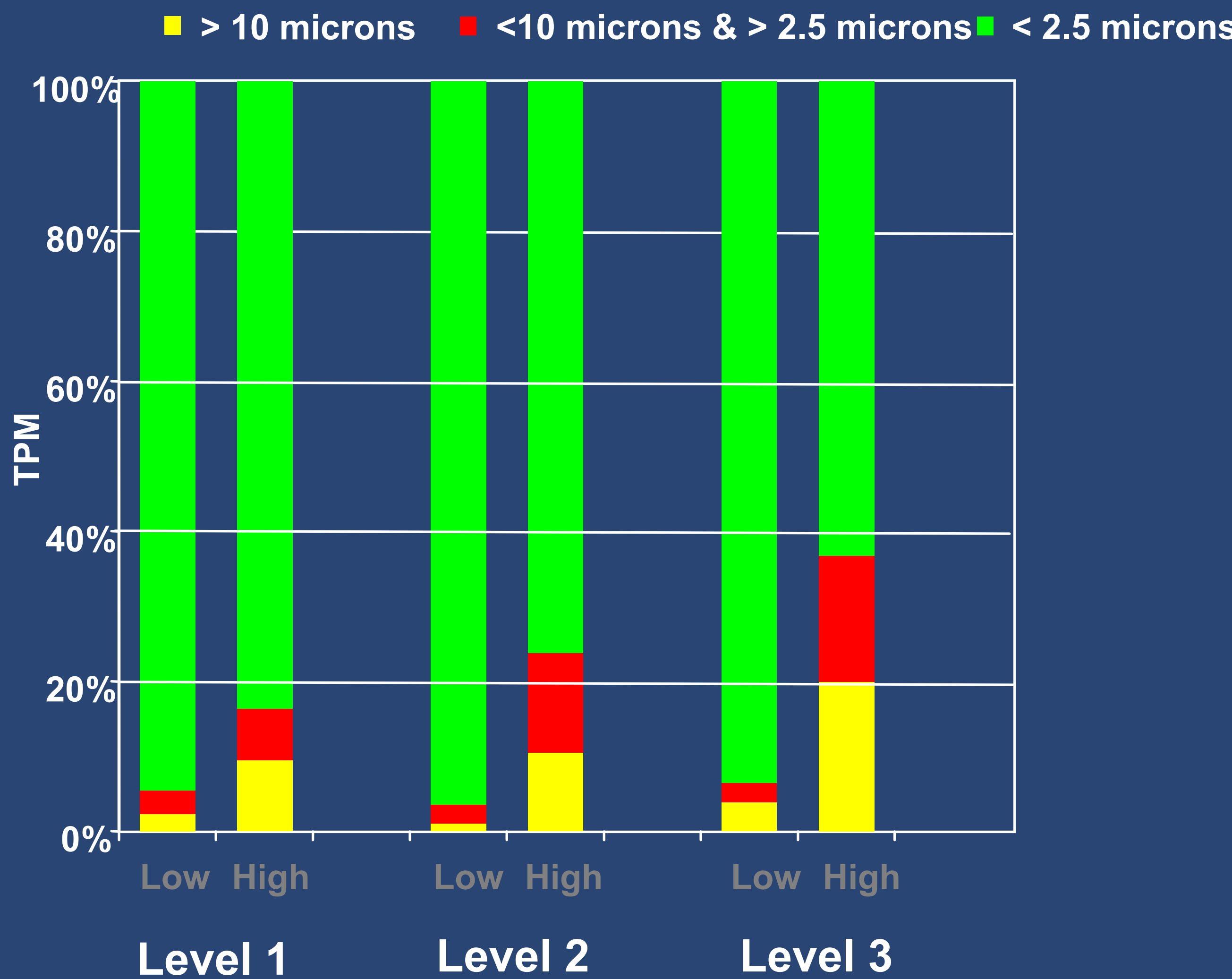
Database of Run Conditions

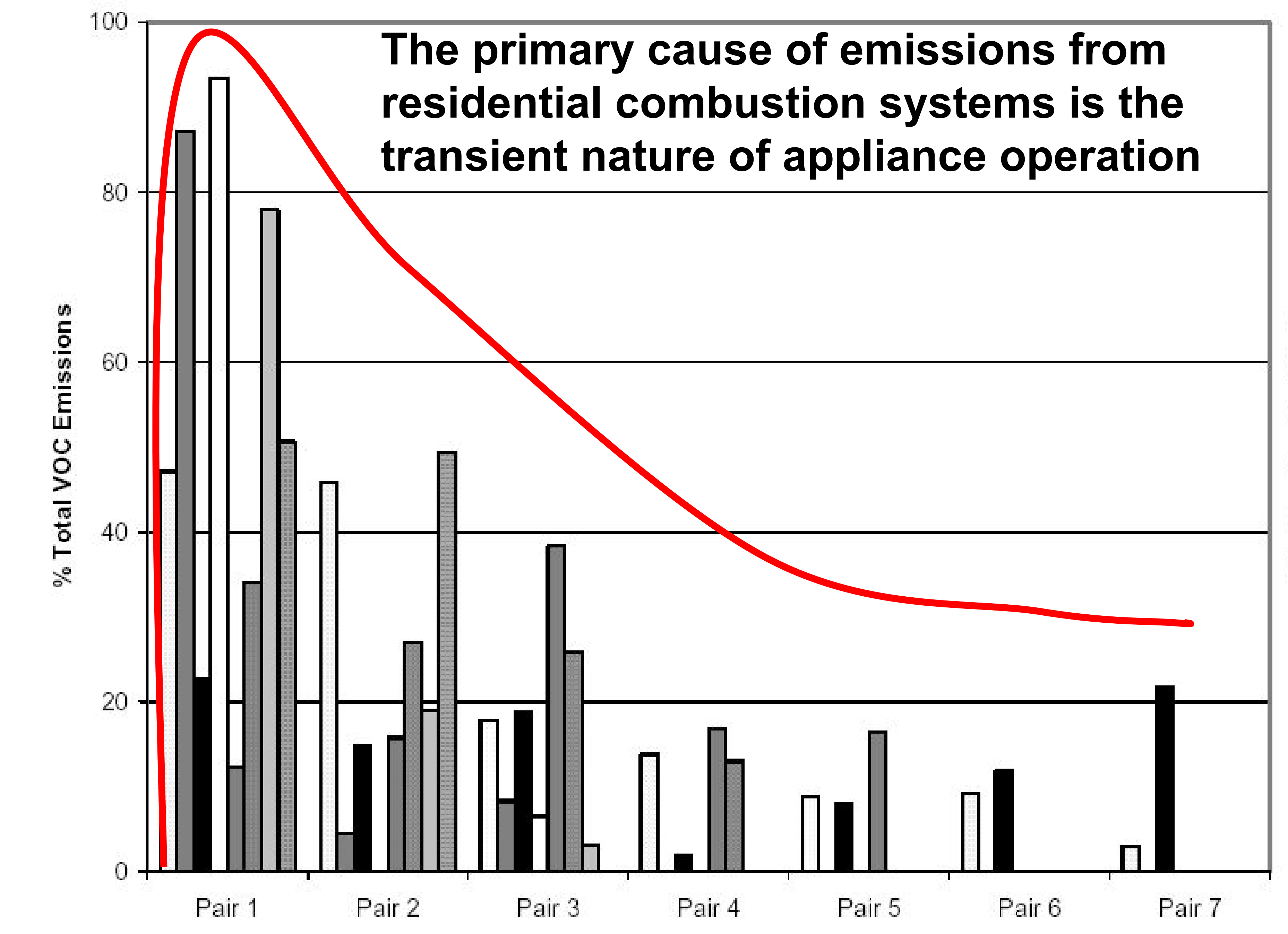
Appliance Type	Dry Fuel Load (kg)	Dry Burn Rate (kg/hr)	Flue Conditions			Appliance Efficiency (%)
			Temp. (°C)	CO_2 (%)	CO (ppm)	
Level 1	5.36	1.78	150	7.9	14165	61.8
Level 1	5.48	3.16	251	9.2	8922	64.6
Level 2	3.61	1.78	150	8.5	11729	57.1
Level 2	3.62	3.04	291	14.6	12472	66.3
Level 3	5.05	1.54	160	7.3	4244	82.8
Level 3	4.73	3.44	295	11.3	3103	71.8
Pellet	4.19	0.84	93	6.5	88	85.6
Pellet	6.98	1.40	139	13.3	65	85
Pellet	6.79	1.36	135	13	50	90.6

Effect of Appliance Design on PM

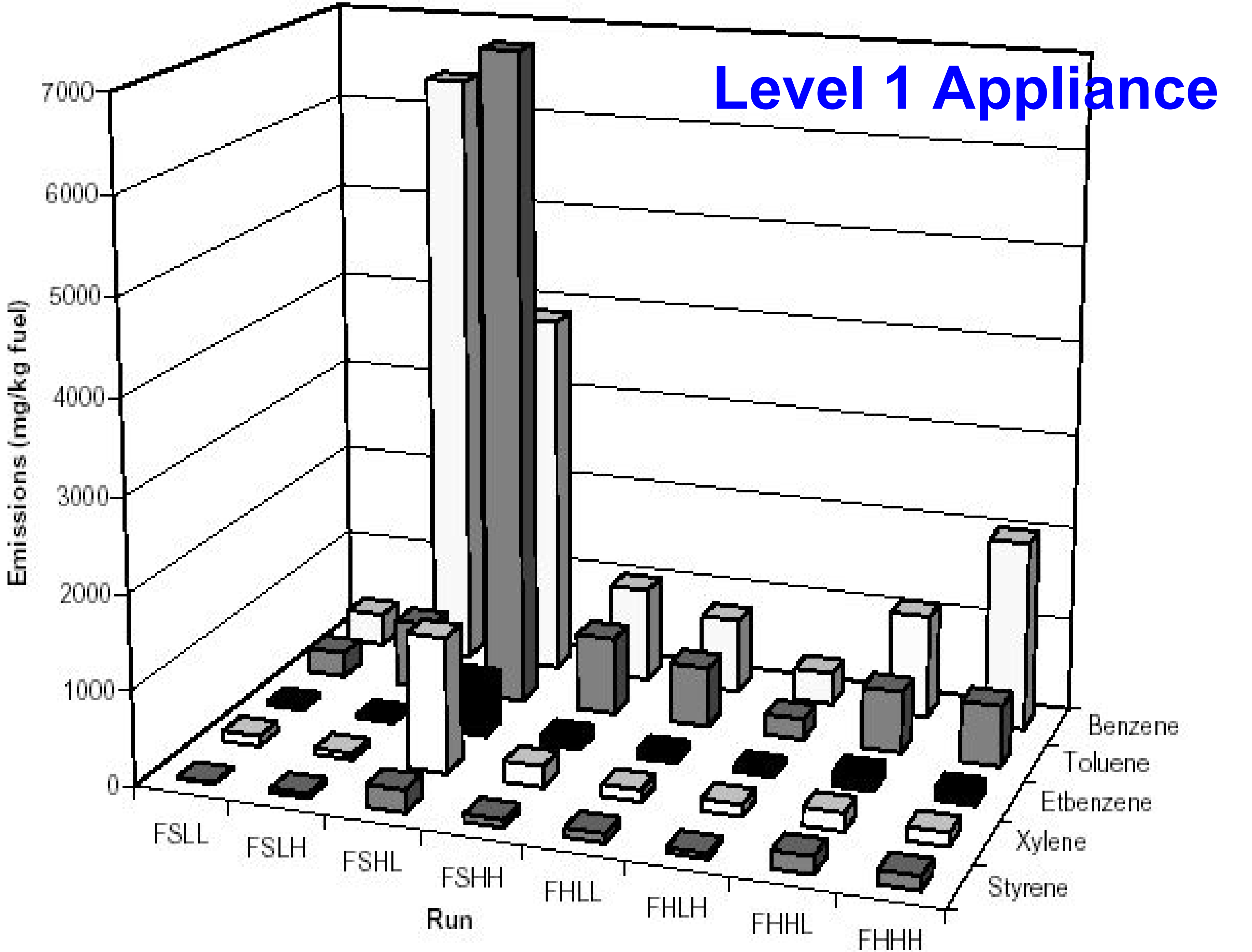


PM Size Distribution



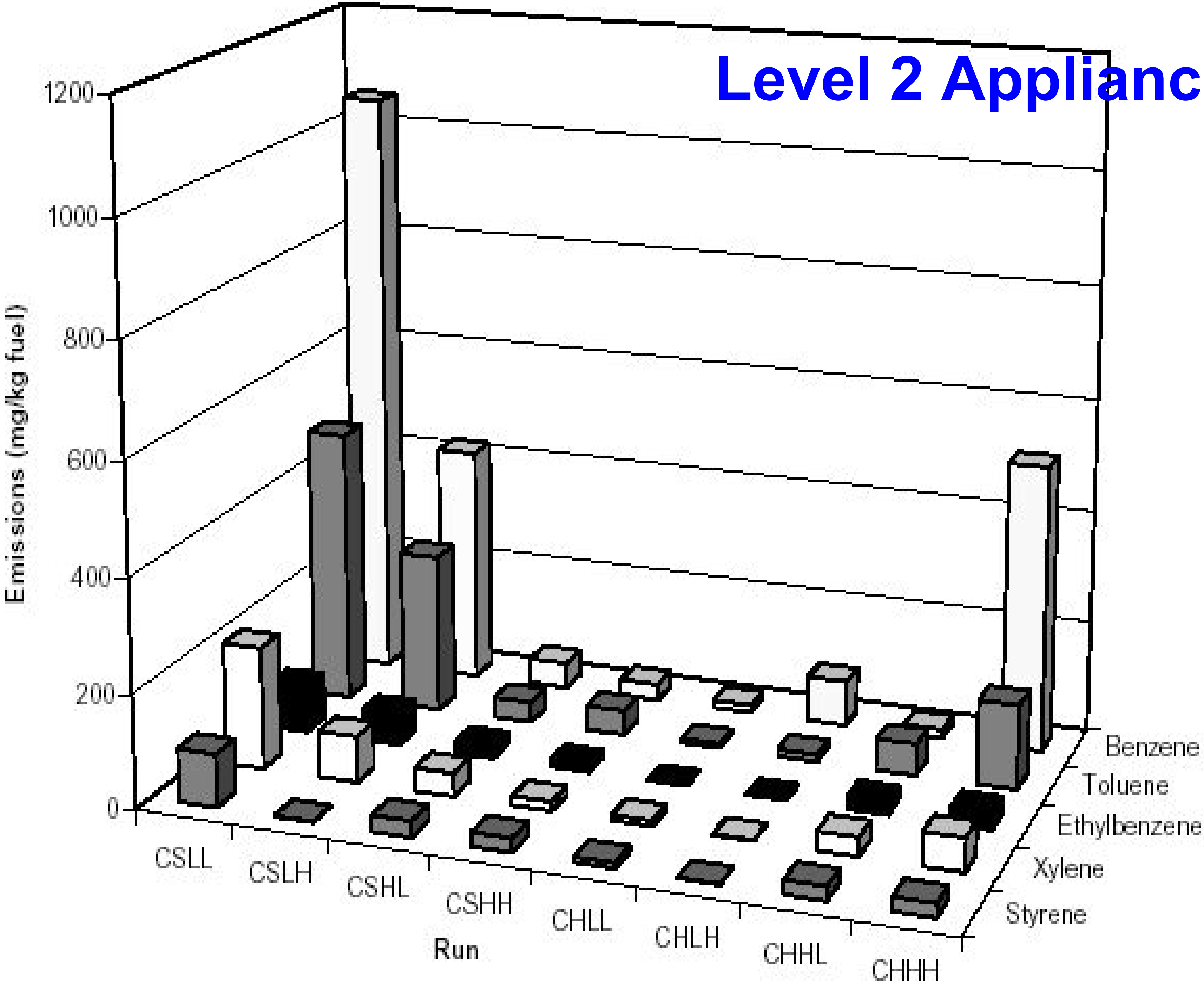


The primary cause of emissions from residential combustion systems is the transient nature of appliance operation
% Total VOC Emissions
100
80
60
40
20
0
Pair 1
Pair 2
Pair 3
Pair 4
Pair 5
Pair 6
Pair 7

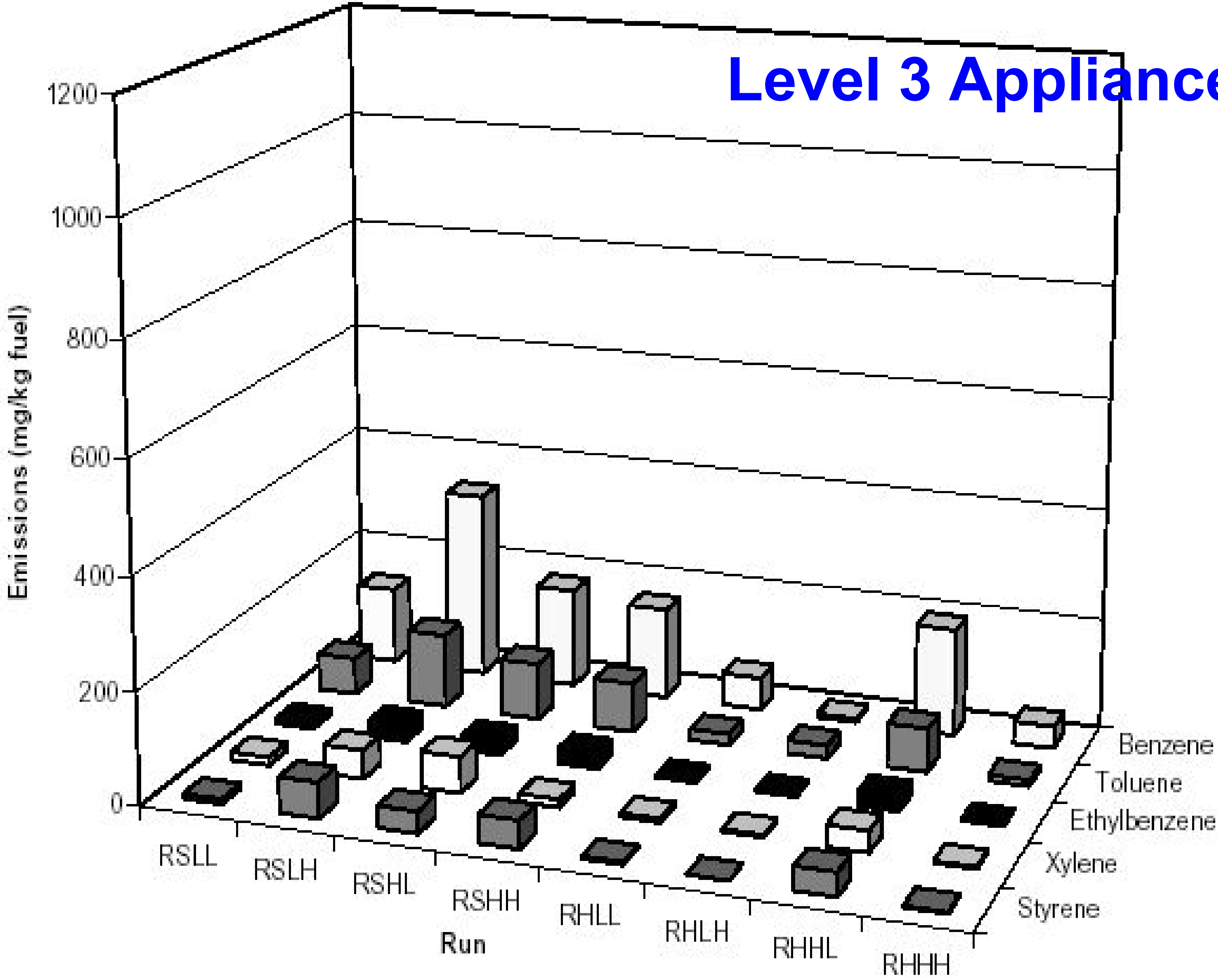


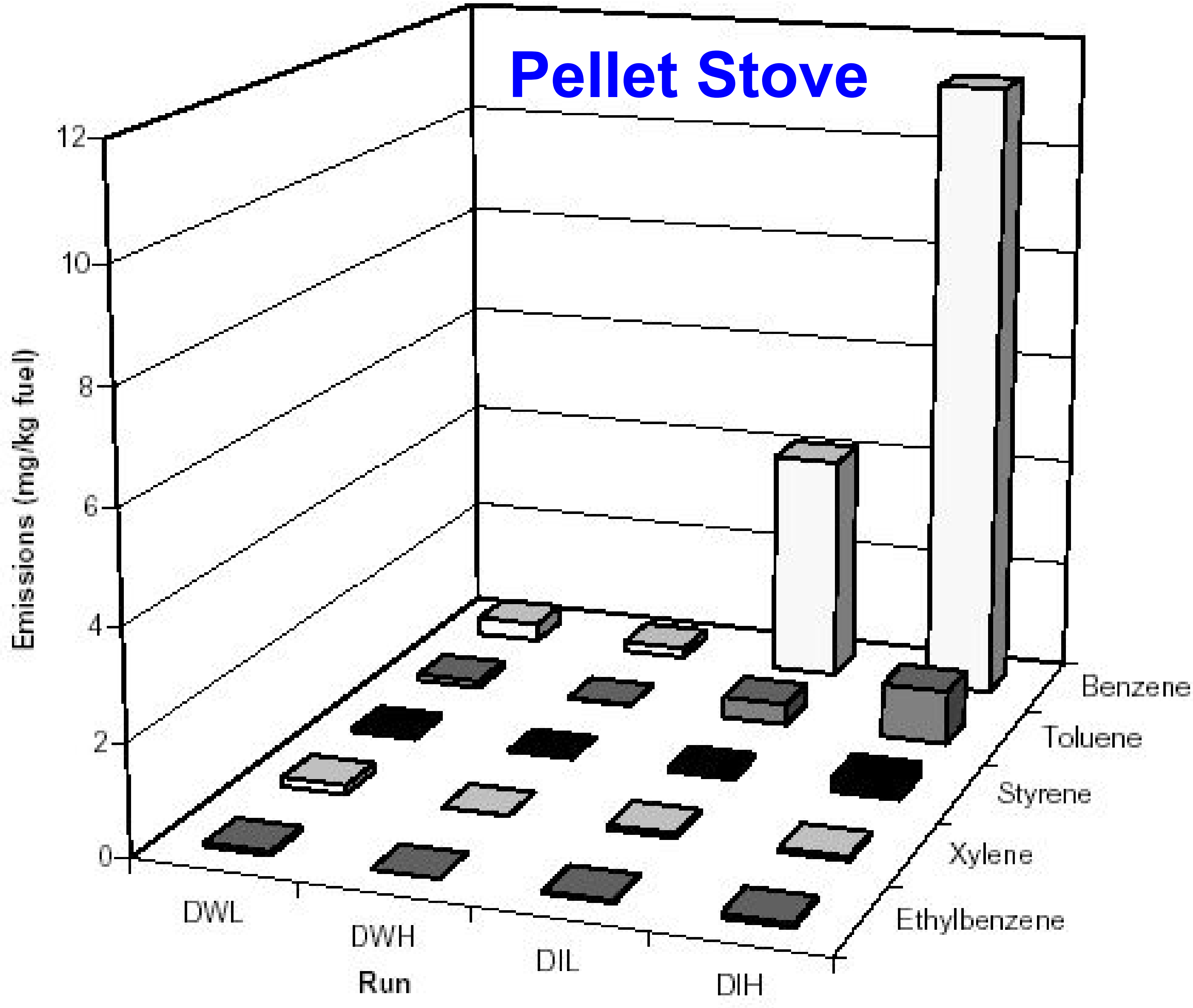
Level 1 Appliance
Emissions (mg/kg fuel)
7000
6000
5000
4000
3000
2000
1000
0
FSLL
FSLH
FSHL
FSHH
FHLL
FHLH
FHHL
FHHH
Run
Benzene
Toluene
Etbenzene
Xylene
Styrene

Level 2 Appliance



Level 3 Appliance



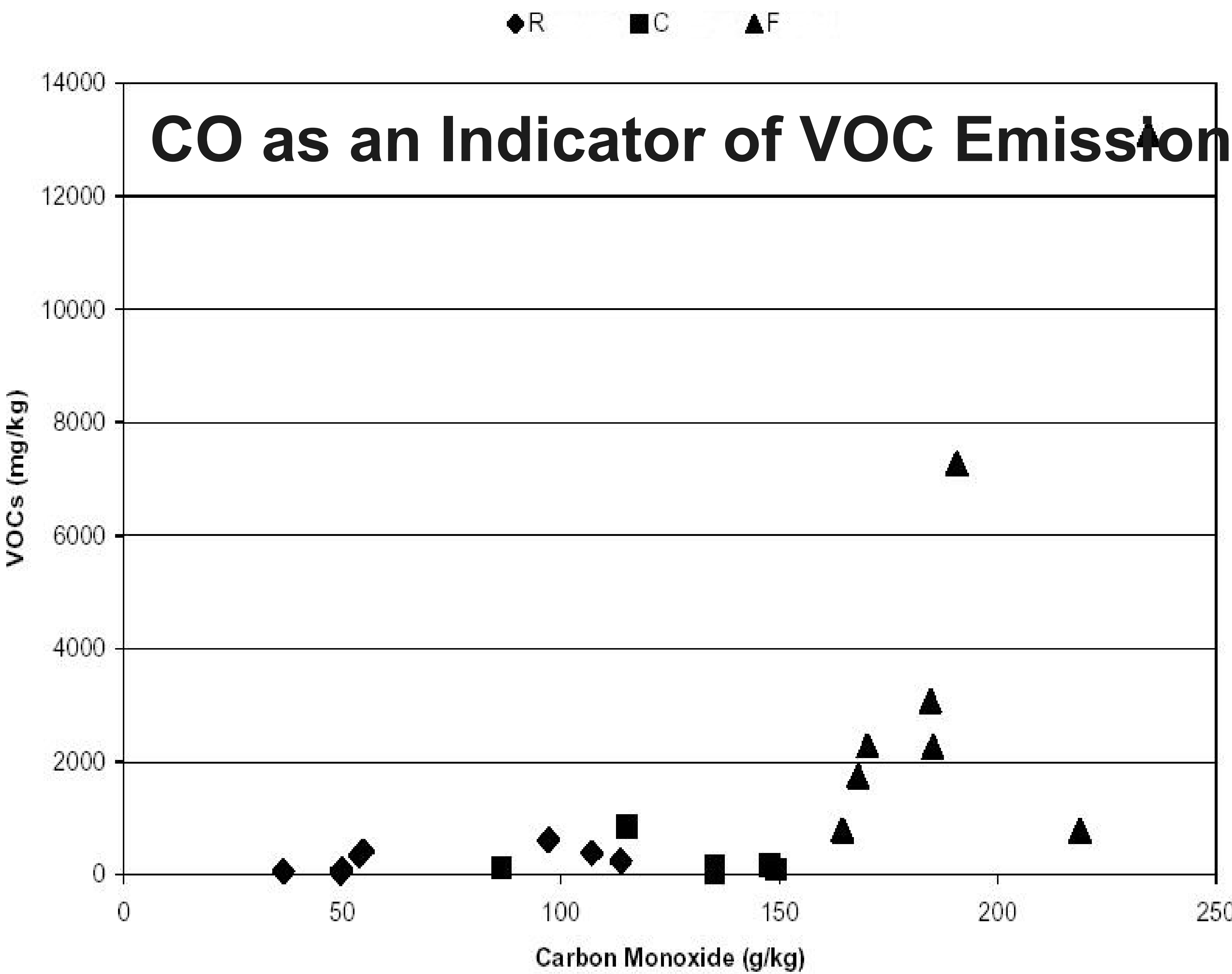


Pellet Stove
Emissions (mg/kg fuel)
0
2
4
6
8
10
12
DWL
DWH
DIL
DIH
Run
Benzene
Toluene
Styrene
Xylene
Ethylbenzene

Transient vs Steady State Operation

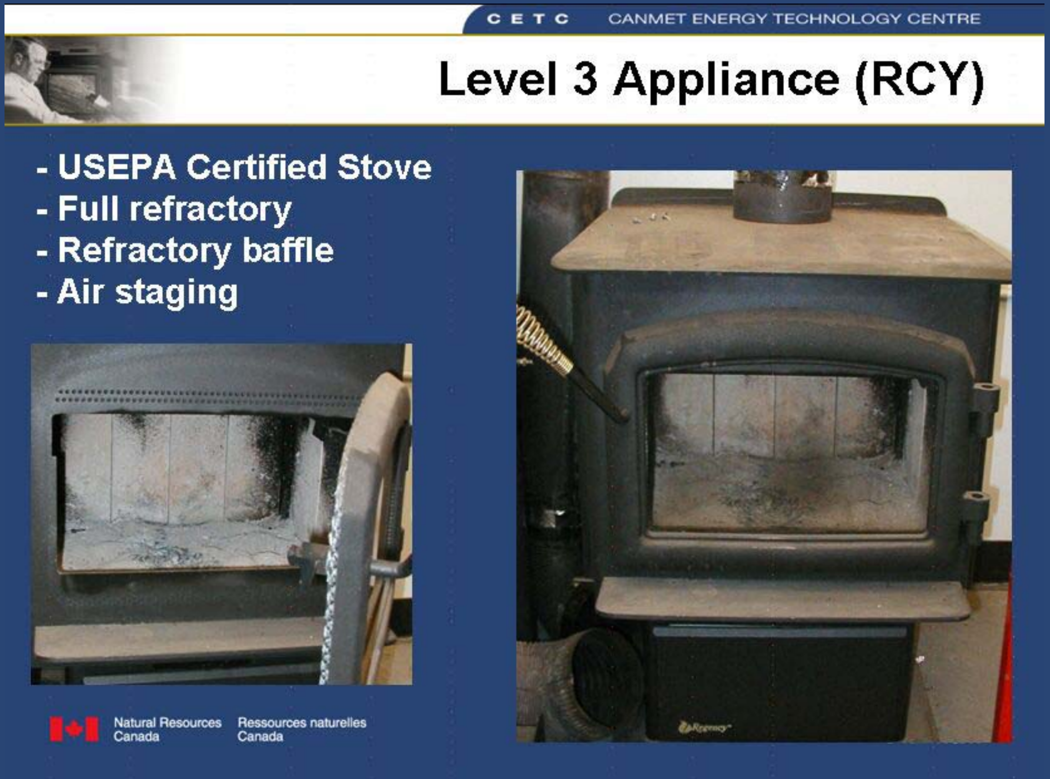
	Cord Wood Stoves	Pellet stove	
Efficiency	55 – 83	85 – 90	%
CO	300 – 14,000	50 – 90	ppm
PM	1.5 – 72.1	0.33 – 0.74	g/kg
VOC	38 – 13,100	0.02 – 13	mg/kg

CO as an Indicator of VOC Emissions

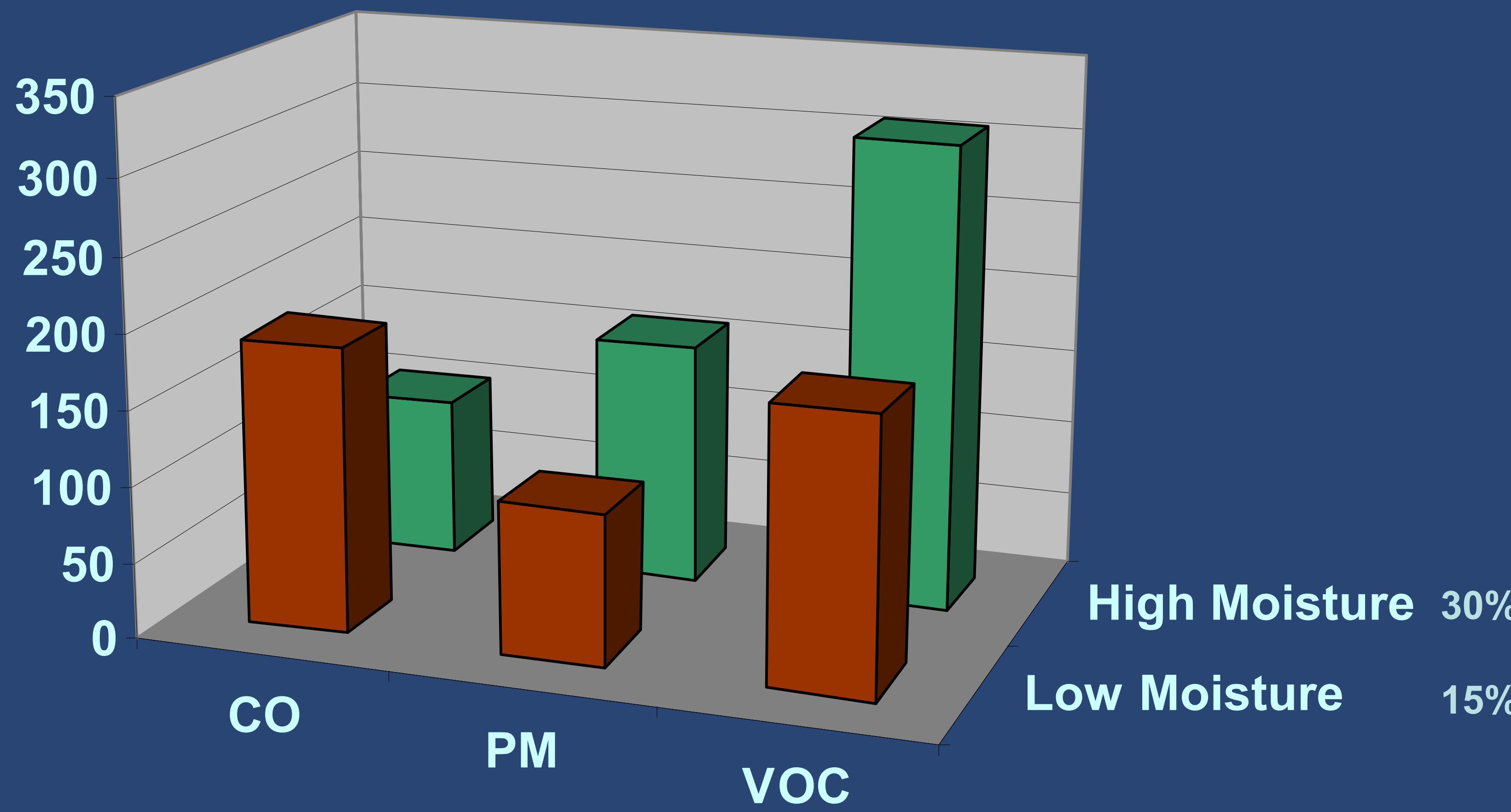


Hazardous Emissions

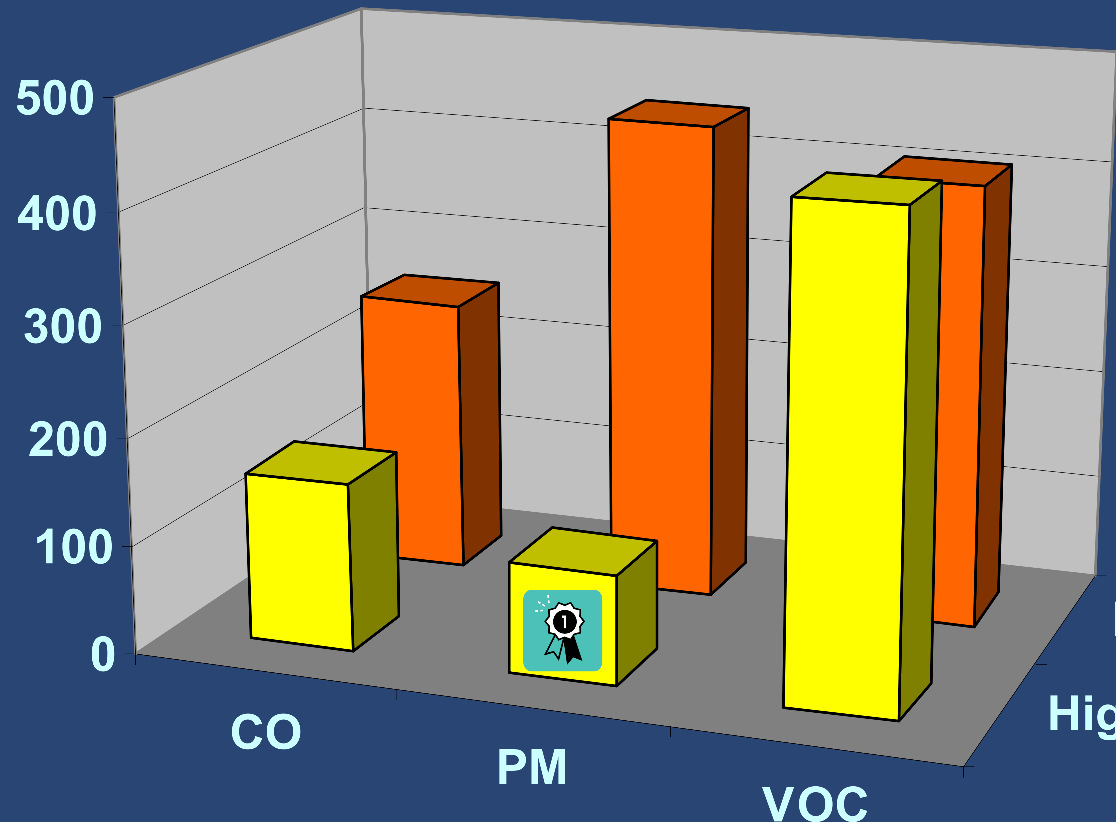
Appliance design is by far the most important factor in reducing hazardous emissions.



Effect of Moisture on Emissions



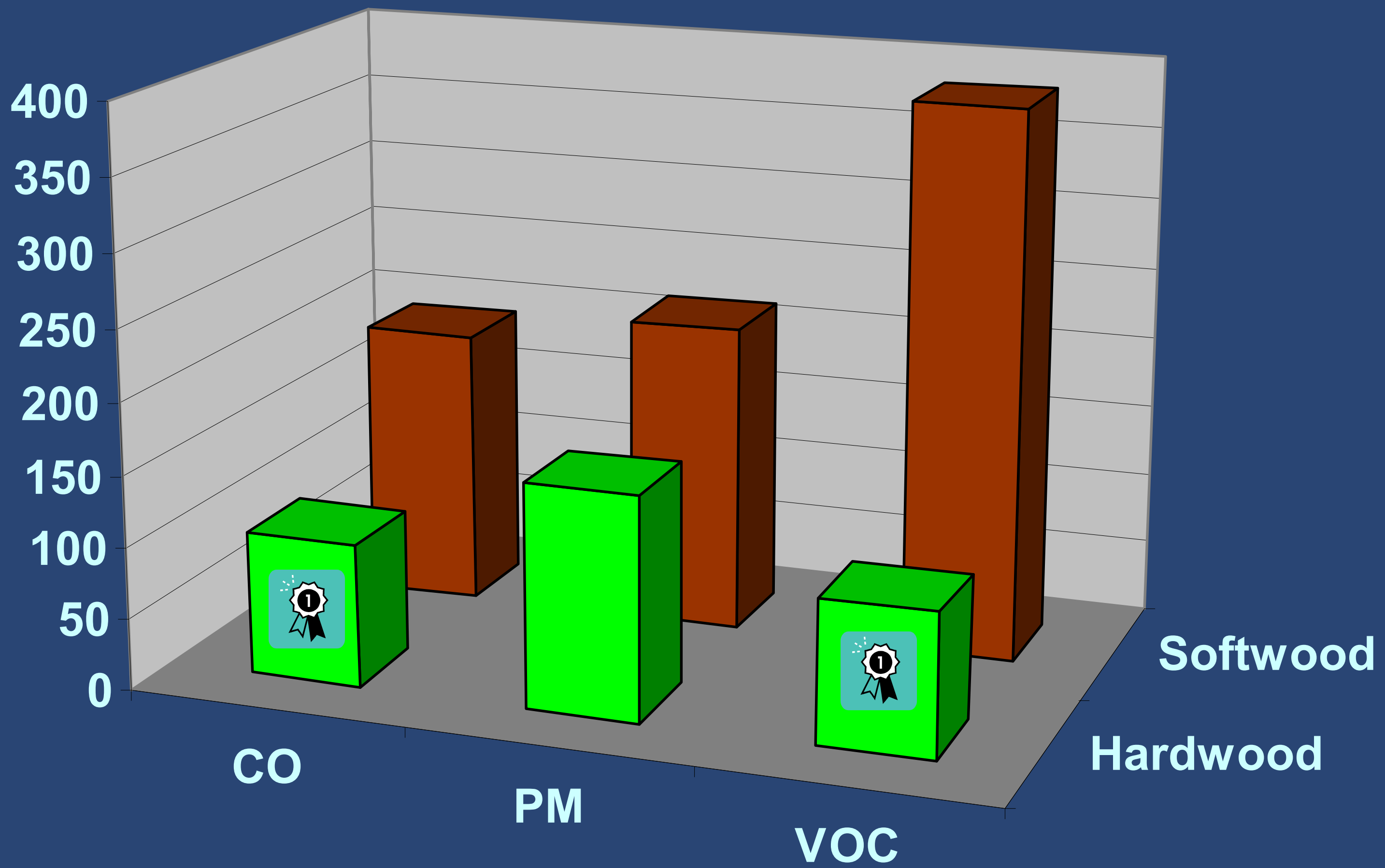
Effect of Firing Rate on Emissions

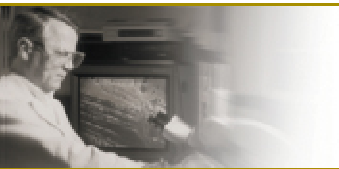


Low Burn Rate 1.5 kg/h

High Burn Rate 3 kg/h

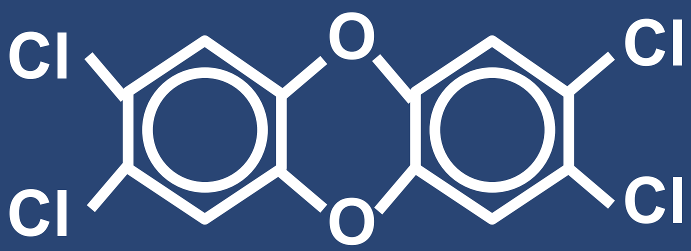
Effect of Wood Type on Emissions





Dioxins and Furans

Dioxin (PCDD)



In 1999 Environment Canada identified residential wood use as a major source of dioxins and furans (PCDDs and PCDFs).

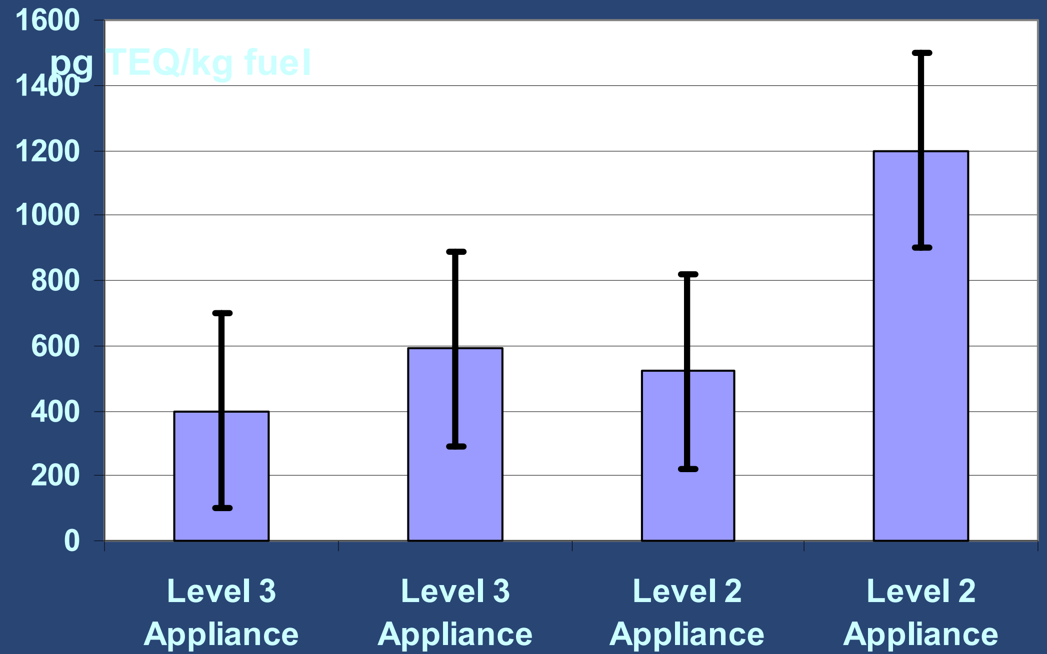
Furan (PCDF)

Environment Canada research however indicated that additional testing was required to verify exisiting data and better understand PCDDs and PCDFs formation in residential systems.

Dioxins and Furans

Due to test conditions with large run-to-run differences and large uncertainty ranges, no conclusions regarding the effect of woodstove type or operating conditions can be made from a series of 8 PCDD/F tests.

The average total PCDD and PCDF emission factor was 669 pg TEQ/kg dry fuel. This value is consistent with results from other studies.



Comparison with other studies

Study	Average Emission Factor (pg TEQ/ kg dry fuel)
NRCan	669
Gullett *et al.*[5] & Crouch and Houck [6]	250
EC[2]	677
Vikelsoe *et al.*[7]	1900

Conclusions

- Residential wood-burning PM is composed primarily of $PM_{2.5}$
- The most prevalent VOC compounds are BTEX (benzene, toluene, ethylbenzene, xylene) and styrene. Most of the other compounds analyzed for were not present above the method detection level.
- Of the VOCs detected, cordwood stoves emissions were composed primarily of benzene (48%) and toluene (28%).
- Additional protocol development is needed to allow detailed study of dioxin/furan formation
- Advanced technology appliances, such as pellet and certified cordwood stoves, produce substantially less hazardous emissions than conventional cordwood stoves.
- The use of hardwood as the fuel substantially reduces emissions as compared to softwood fuel.
- In general, lower fuel moisture and high burn rates result in lower emissions but there is no consistent effect on all hazardous emissions.

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CLEAN ENERGY TECHNOLOGIES

Thank you

Fernando Preto
CETC – Ottawa
preto@nrcan.gc.ca
+1-613-996-5589

Canada

Annex 4. A systematic process identification as a tool for combustion control design

Kai Pietila, VTT, Finland

A systematic process identification as a tool for combustion control design

Kai Pietilä
VTT Processes
kai.pietila@vtt.fi
+358 20 722 2637

Contents of the study

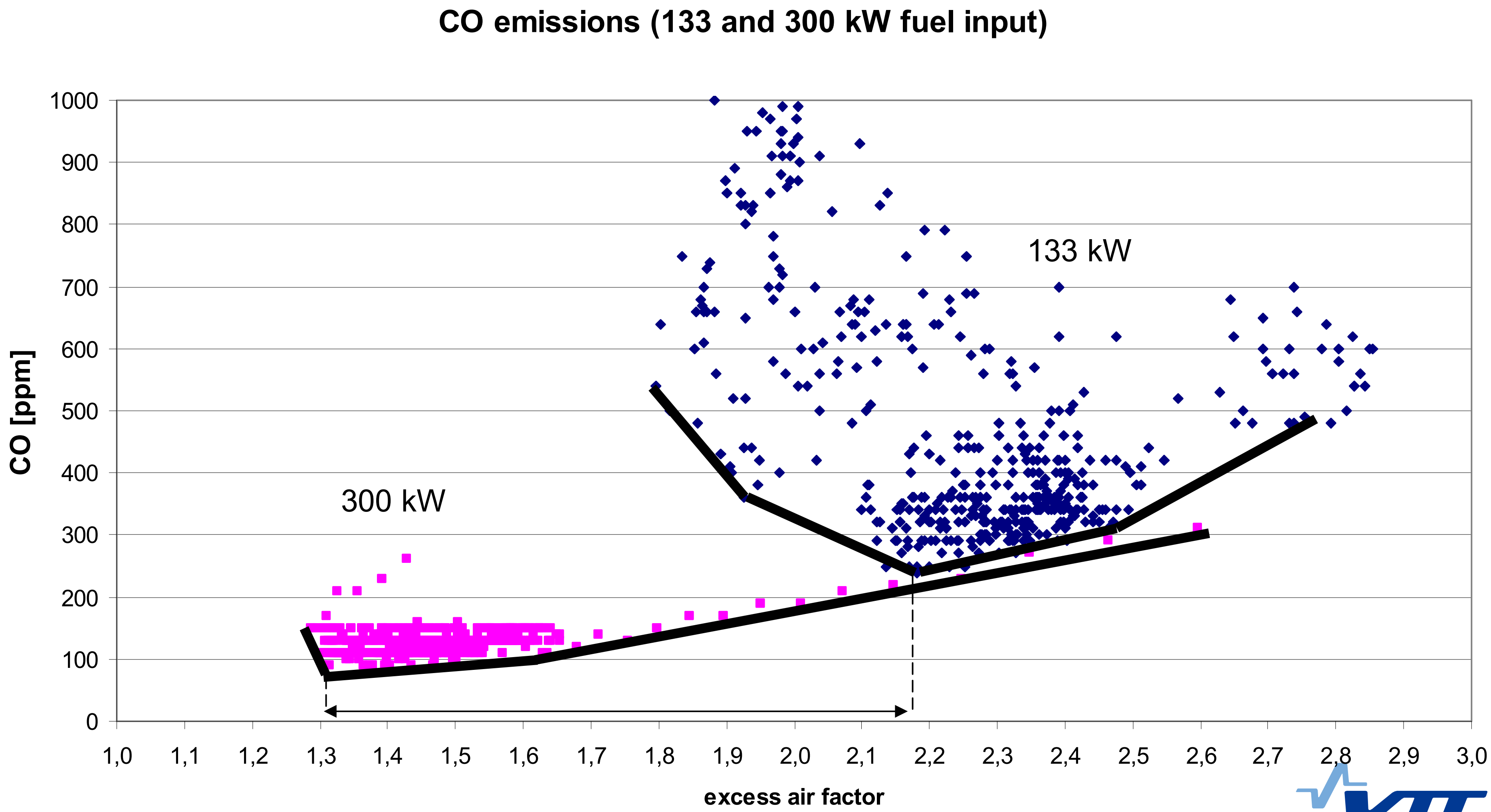
1. Preliminary tests at different operating points of the boiler
2. Systematic process identification using design of experiments
   - Control criteria
   - Identification of important control variables and disturbances, and interaction between variables
3. Step response experiments to determine dynamical behaviour of process
   - Control strategy
4. The possibility of using soft sensors to estimate important variables
   - O_2, CO_2, CO, heat output

Test burner

- 300kW
- Fuel: wood chips
- Fuel feed: 2 screws
- Air feed: 3 fans

Some results of the preliminary tests

Case: a 300 kW boiler, fuel: wood chips



Identification of important variables

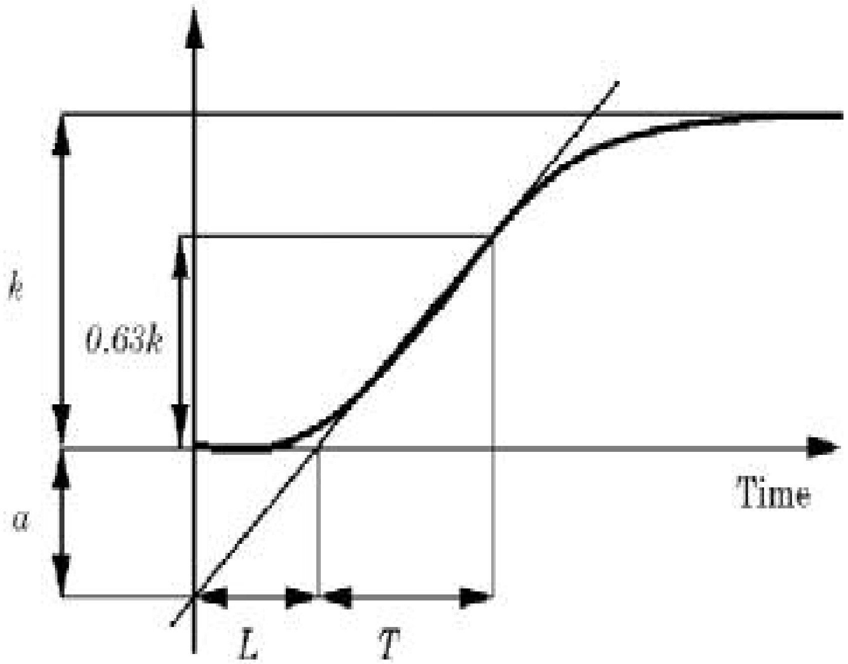
Case: a 300 kW boiler, fuel: wood chips

- 2^{k-1} fractional factorial design of experiments
- Fuel moisture, fuel power, total air feed, primary and secondary air ratio
- Each variable was tested on 2 levels
- Center point tests were made before and after the tests to define time variance of the boiler during test period
- Results:
  - No drifting in process parameters during tests
  - Primary/secondary air ratio has most effect on CO emissions
  - Heat output can be controlled with fuel power
  - Total air feed and fuel power control the CO_2 concentration in fluegas

Step response tests

Case: a 300 kW boiler, fuel: wood chips

- The dynamics of the boiler were defined using 1st order transfer functions
- Tests were made in three operating points to find the nonlinearities in the process
- Also steps were made in both directions



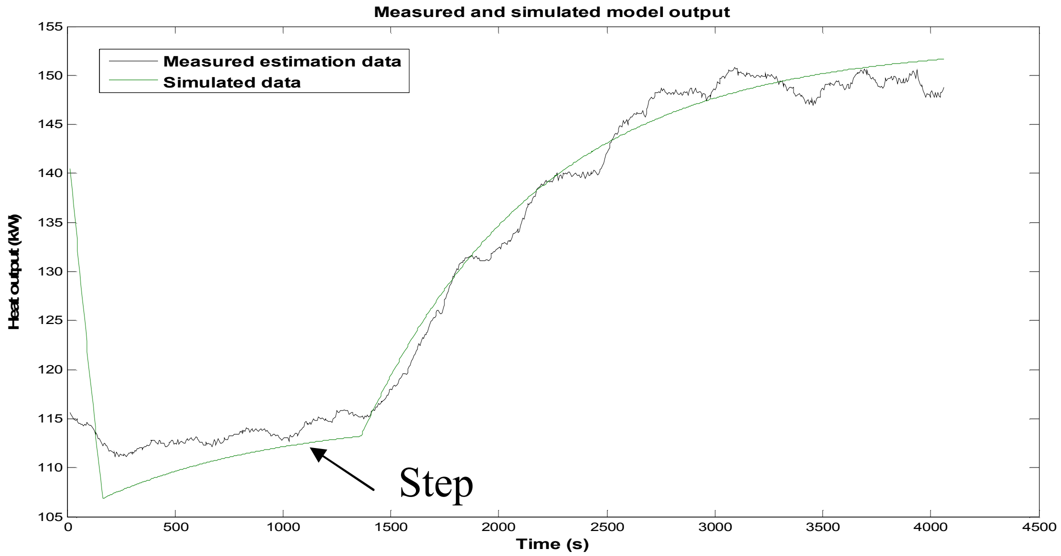
$$G(s) = \frac{Y(s)}{U(s)} = \frac{k}{1 + sT} e^{-sL}$$

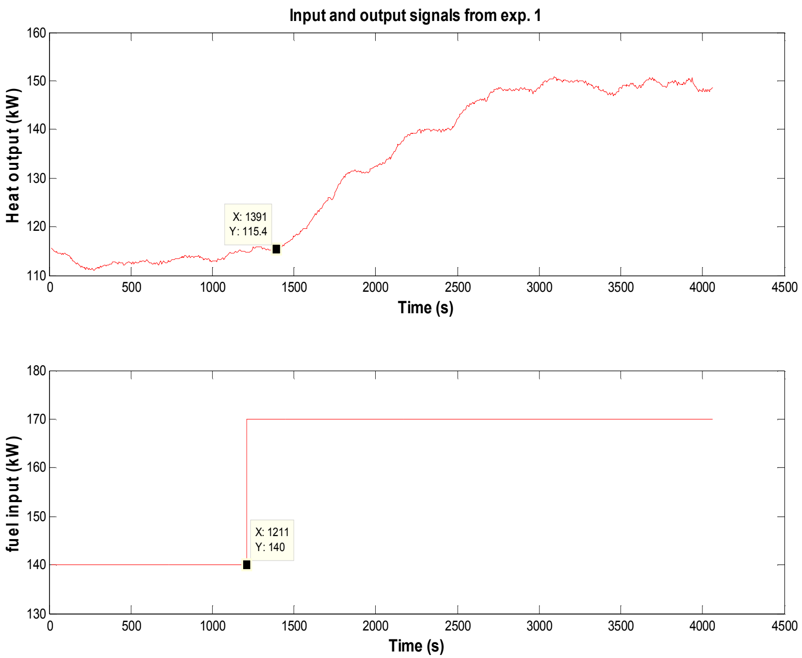
Y is output of the process
U is input of the process
L is dead time (delay)
T is time constant
k is static gain of the process

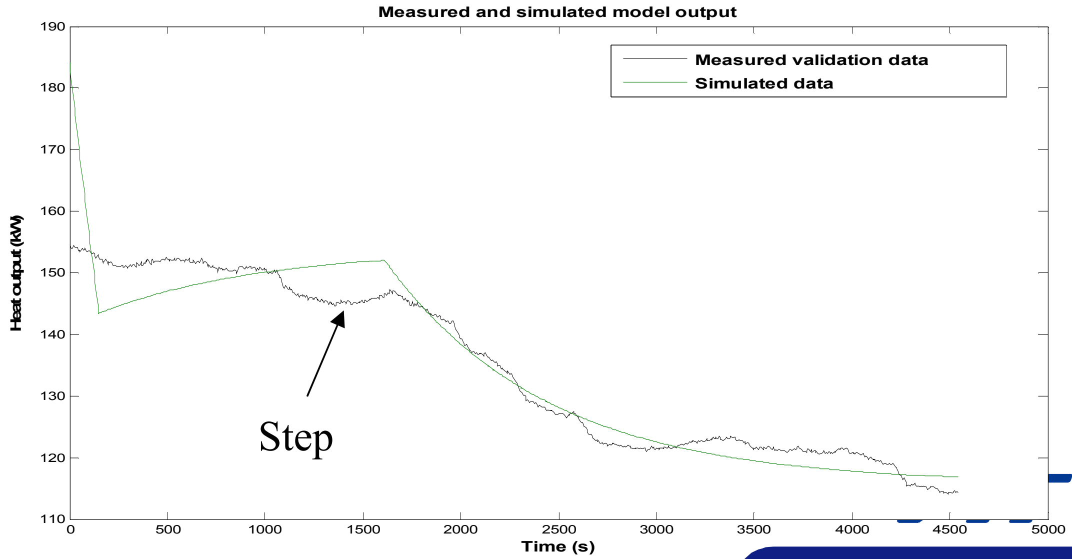
Some results of the step response tests

Response of the heat output to the step change of fuel power

- 30 kW change in fuel power
- Effect in heat output
  - k=1,27
  - T=827 s
  - T_d=150 s



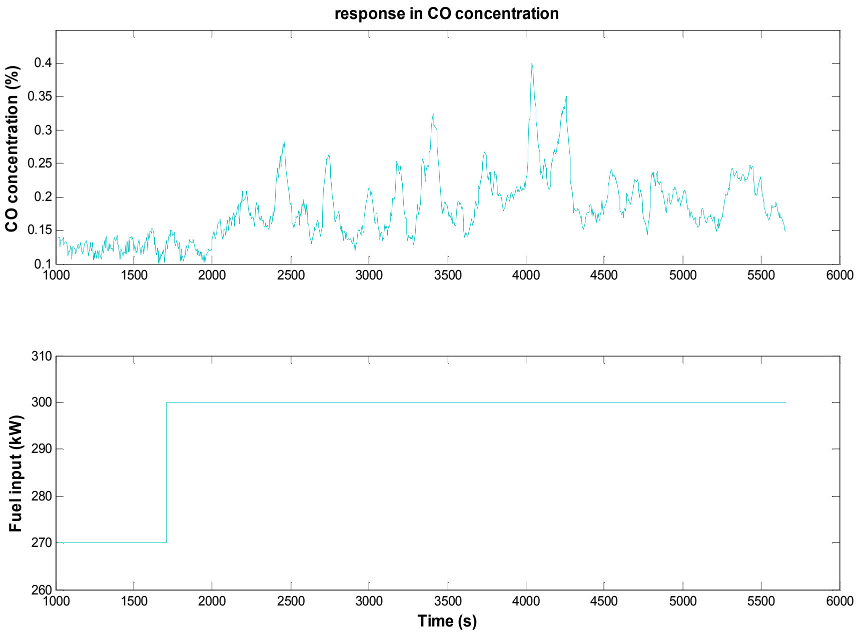


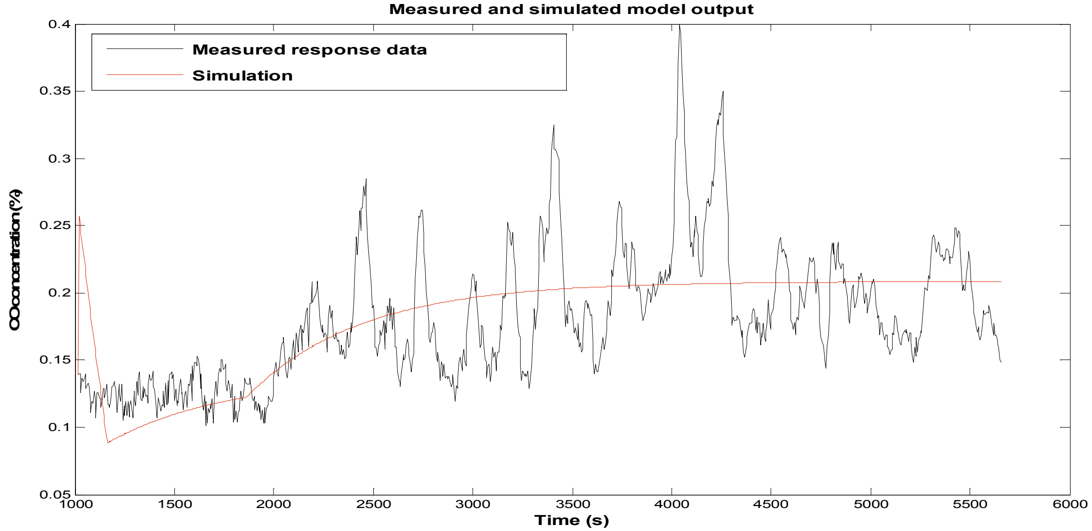


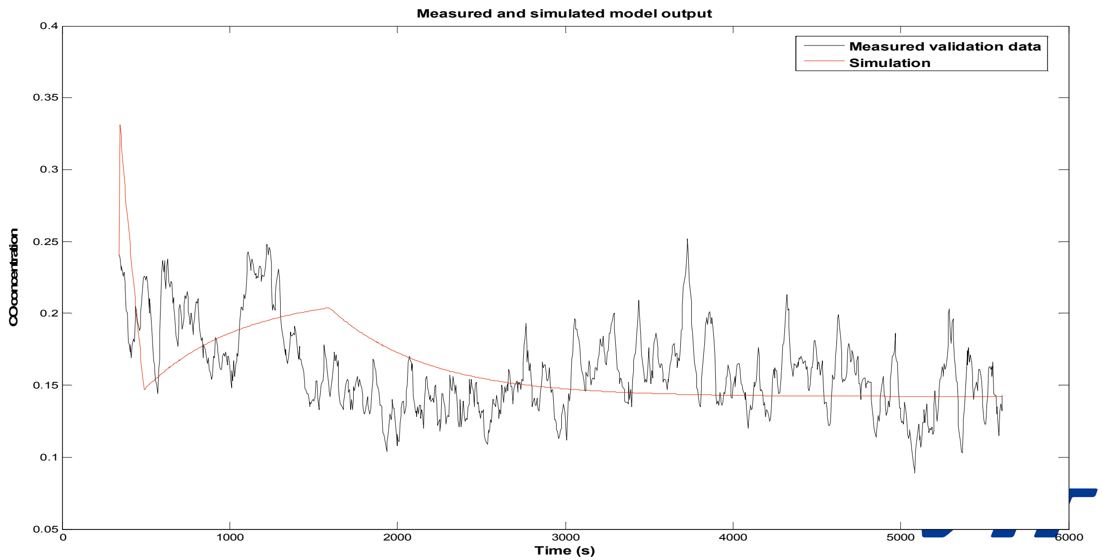
Some results of the step response tests

Response of the CO concentration to the step change of fuel power

- 30 kW change in fuel power
- Effect in CO
  - k=0,002
  - T=577 s
  - T_d=149 s



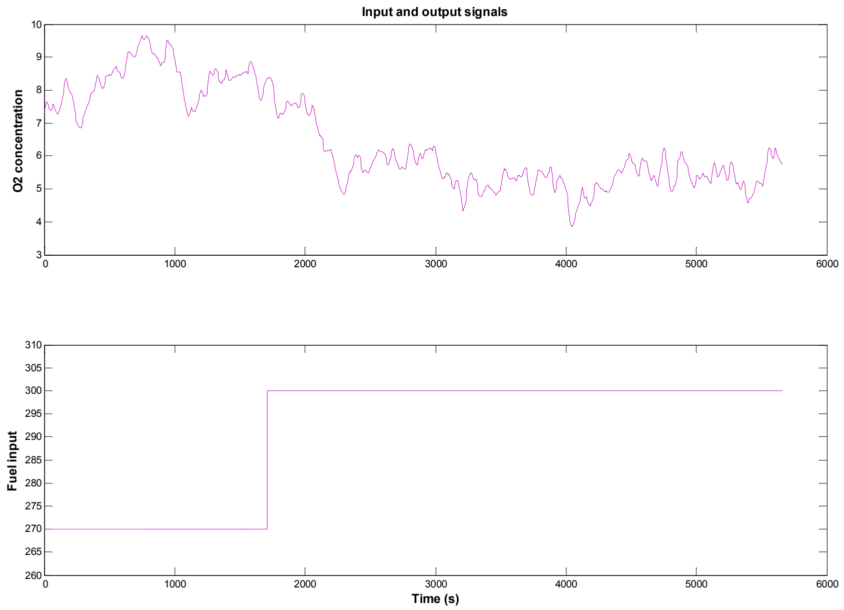


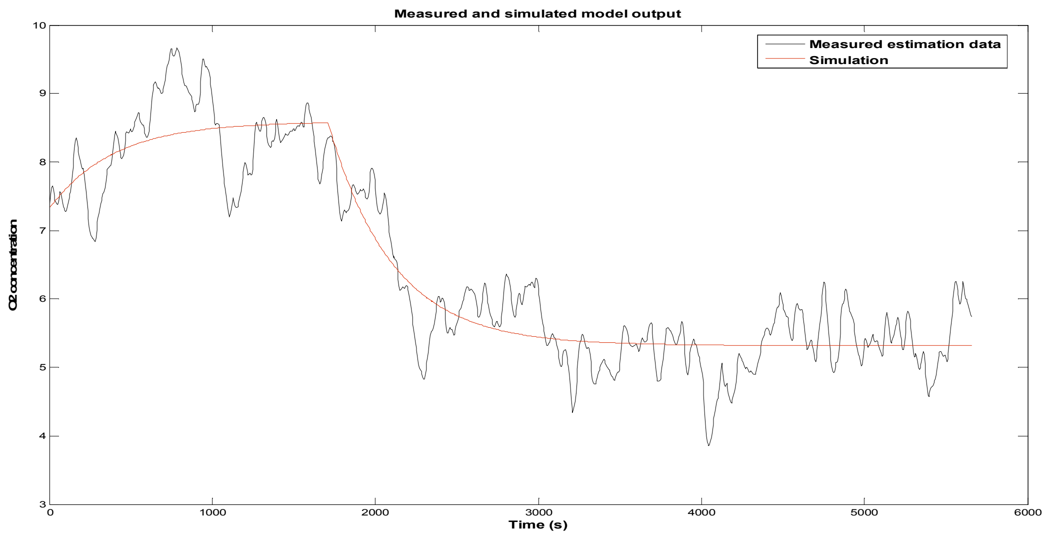


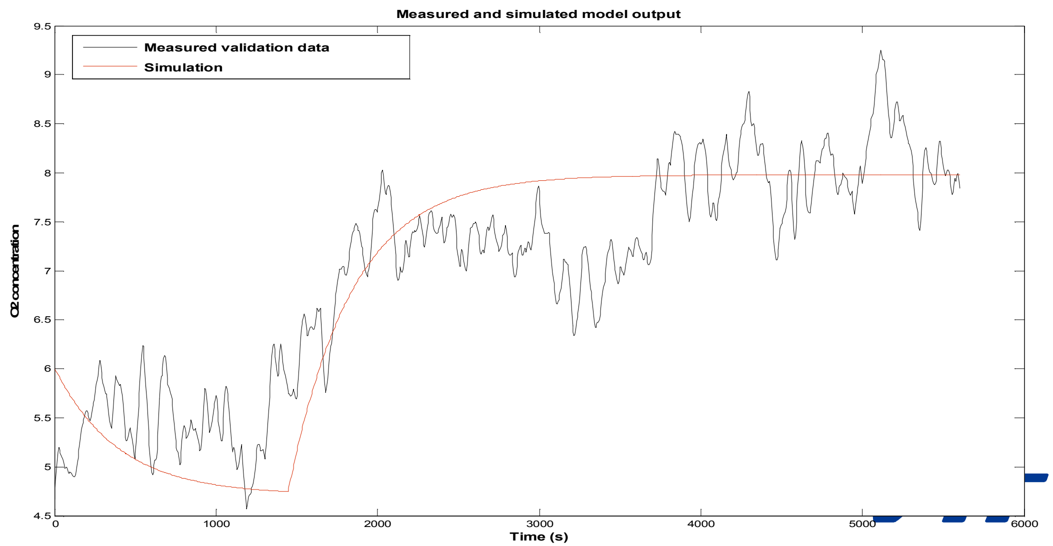
Some results of the step response tests

Response of the O_2 concentration to the step change of fuel power

- 30 kW change in fuel power
- Effect in O_2
  - k=-0,109
  - T=393 s
  - T_d=0 s



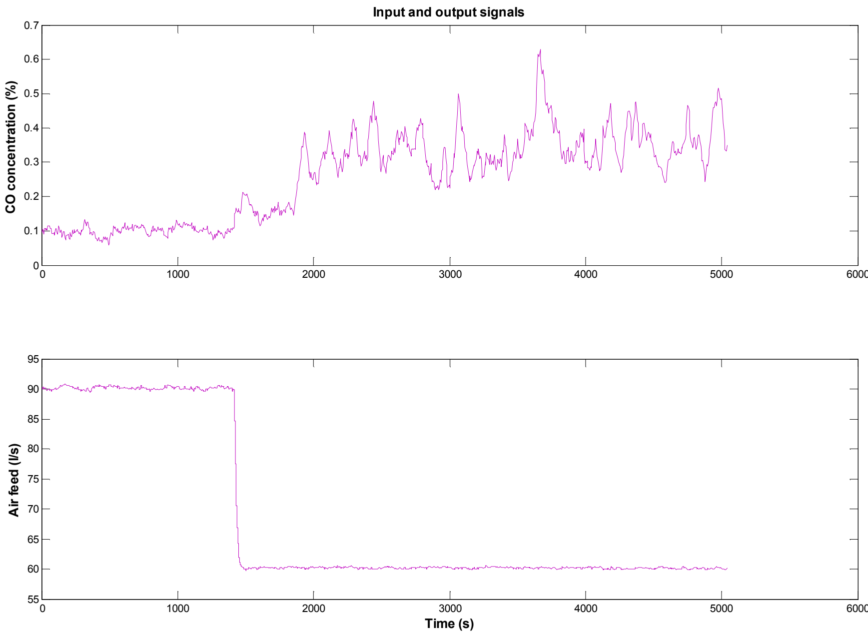


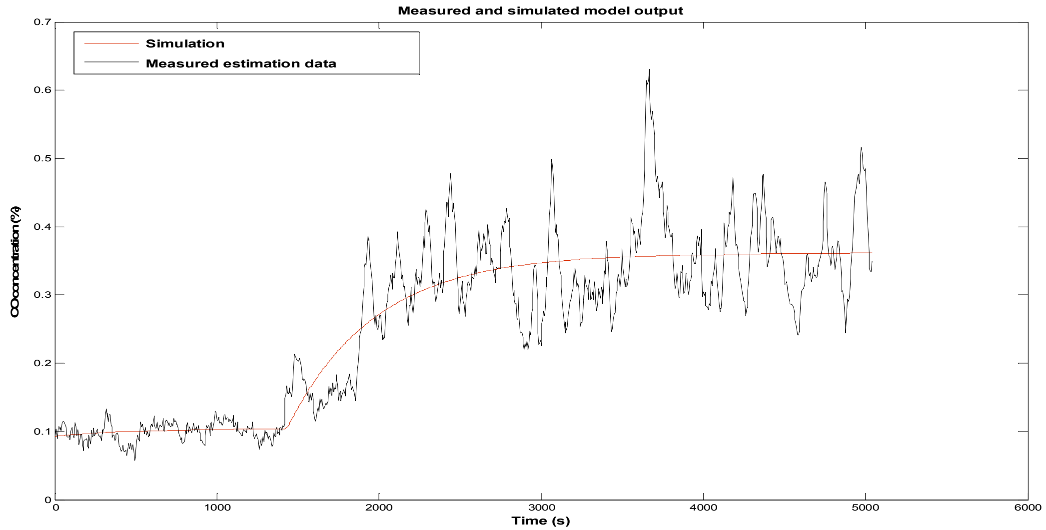


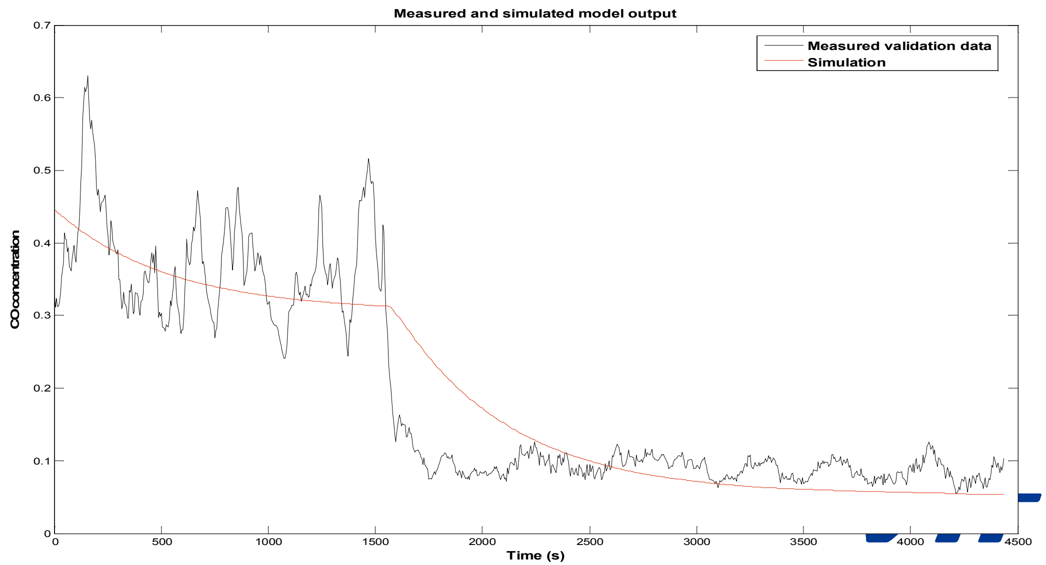
Some results of the step response tests

Response of the CO concentration to the step change of total air feed

- 30 l/s change in total air feed
- Effect in CO
  - k=-0,009
  - T=537 s
  - T_d=0 s



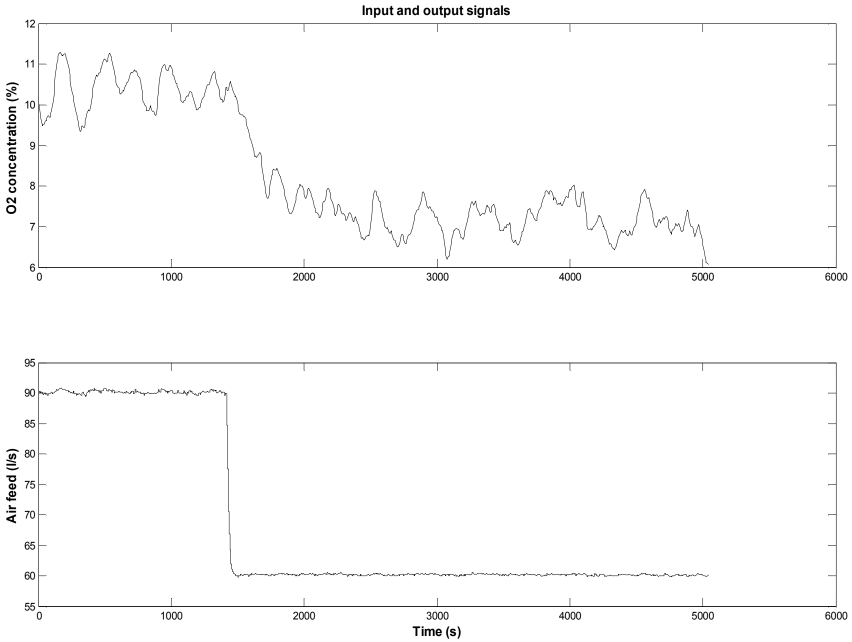


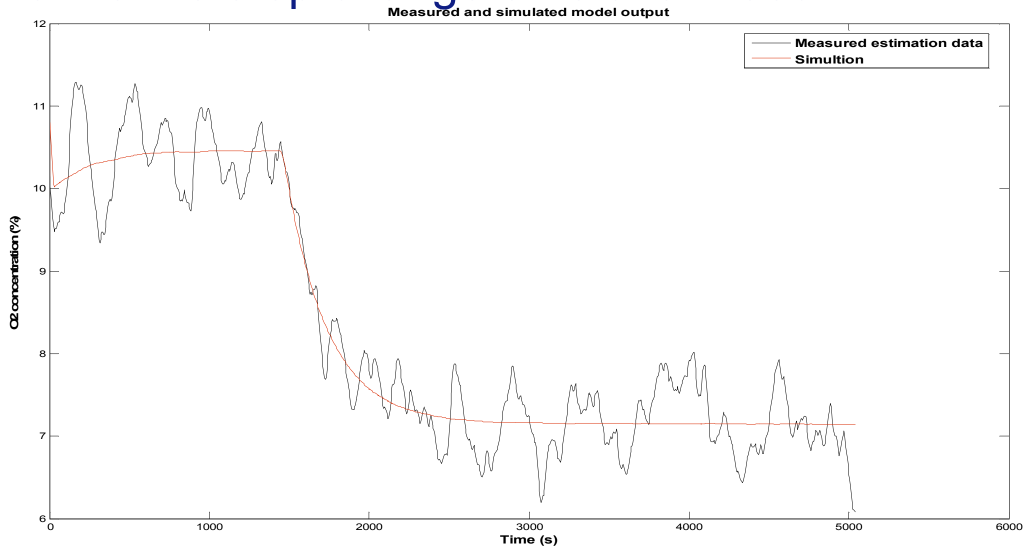


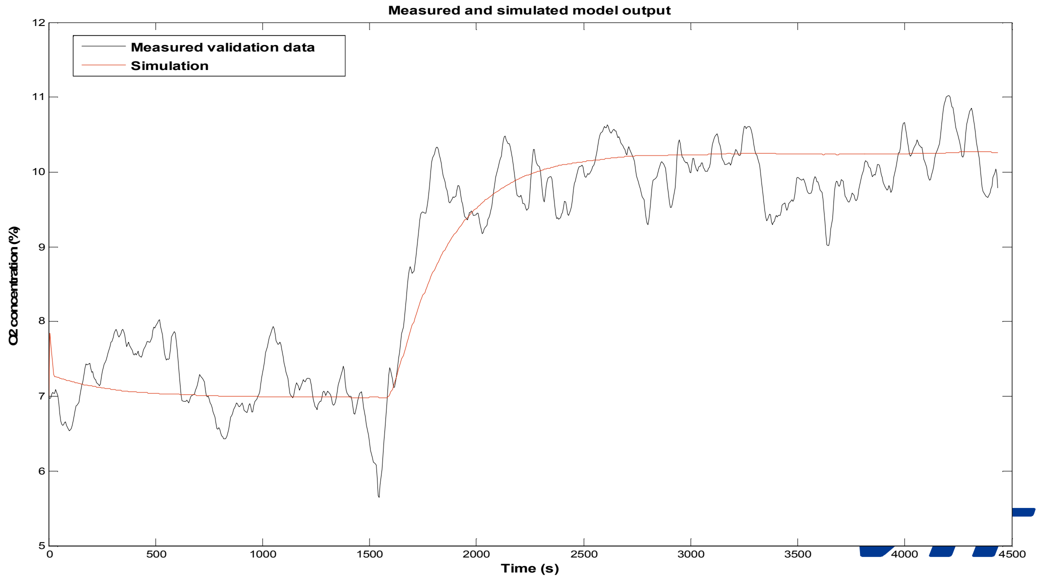
Some results of the step response tests

Response of the O_2 concentration to the step change of total air feed

- 30 l/s change in total air feed
- Effect in O_2
  - k=0,111
  - T=263 s
  - T_d=26 s







Results of the step response tests

Case: a 300 kW boiler, fuel: wood chips

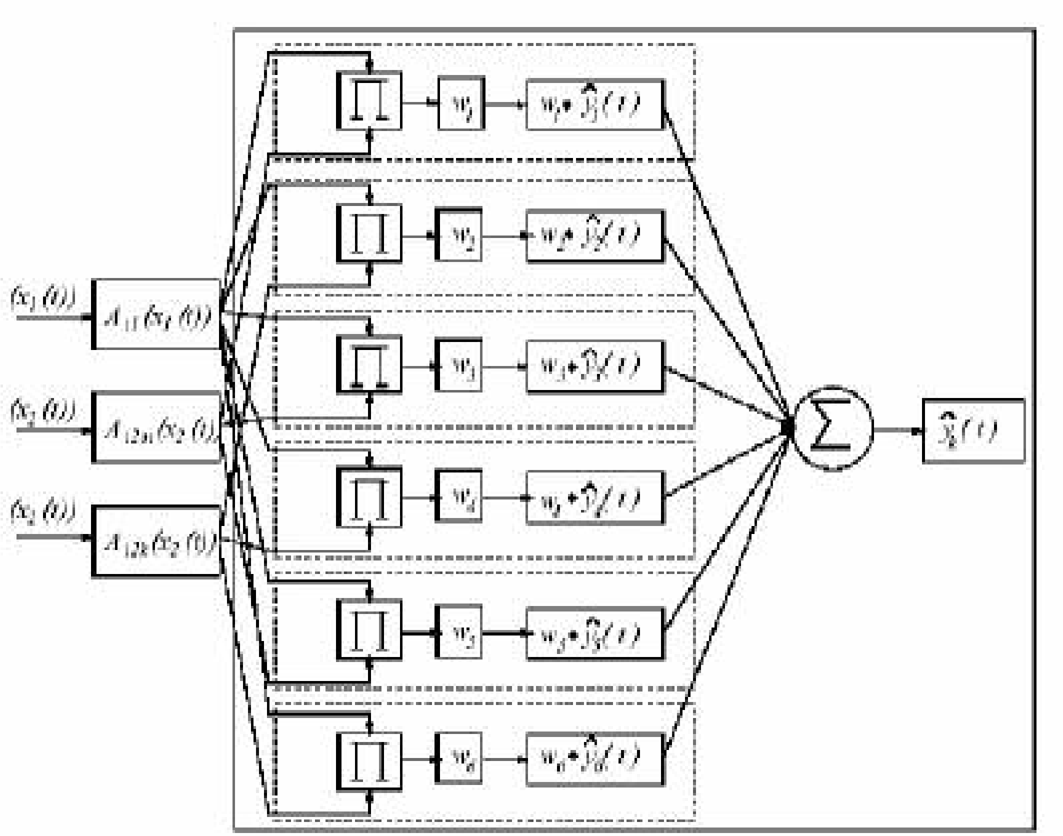
- The behavior of this boiler can be simulated with first order transfer functions
- Separate models have to be created for different power levels (operating points)
- Changes in fluegas components were faster when air feed was increased or fuel feed was decreased
- Heat output behaved the same way in both directions

Soft sensors

- Mika Ruusunen, University of Oulu

- Usually mathematical model(s) of process variables
- Utilisation of simple sensors, sensor fusion
  - Fast response, inexpensive, reliability
- Models developed in this research are based on the Takagi-Sugeno fuzzy model
  - Utilisation of expert knowledge
  - Local linear models for changing operation conditions

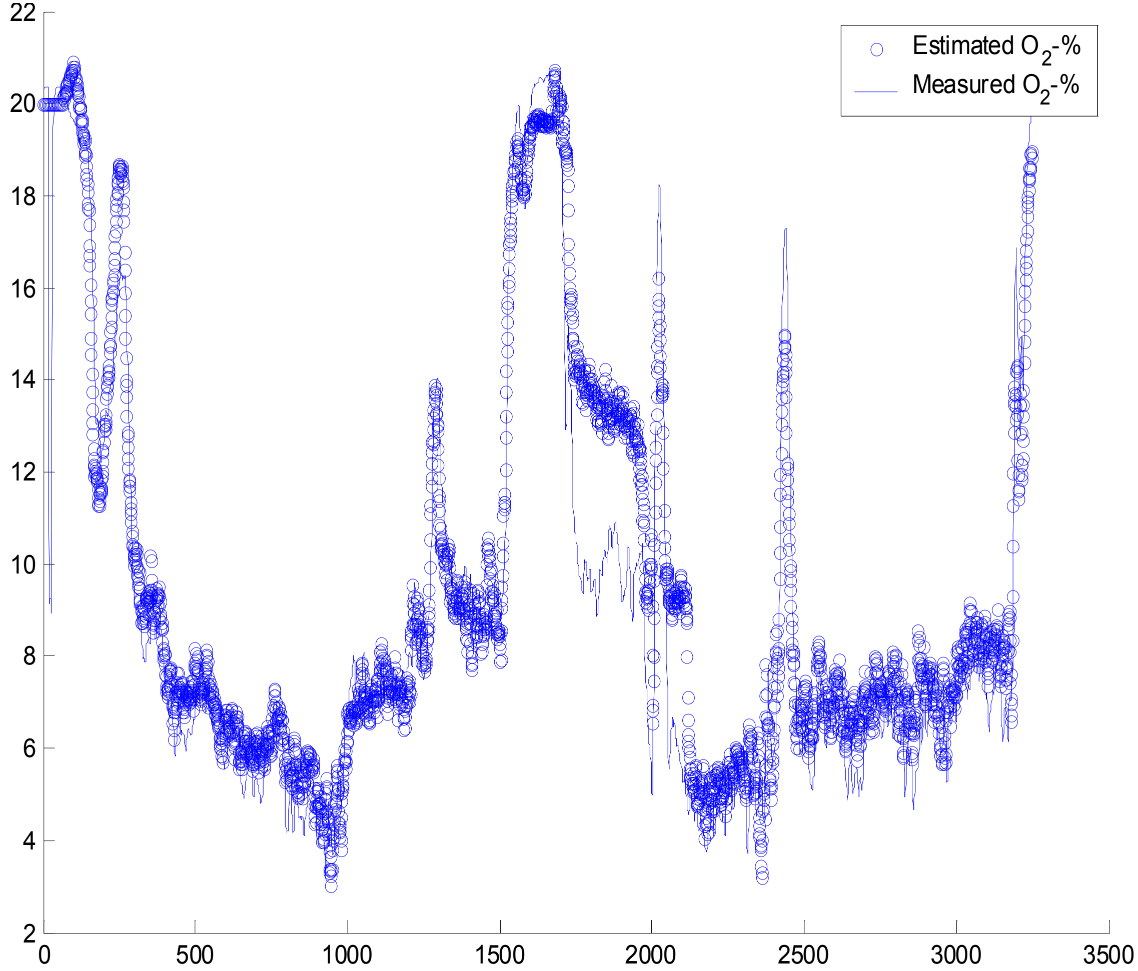
Takagi-Sugeno Model Structure



- R1: IF x1 is {**Ai1**} AND x2 is {**Ai2n**} THEN y1 = **a**1 **x** + b1
- R2: IF x1 is {**Ai1**} AND x2 is {**Ai2k**} THEN y2= **a**2 **x** + b2

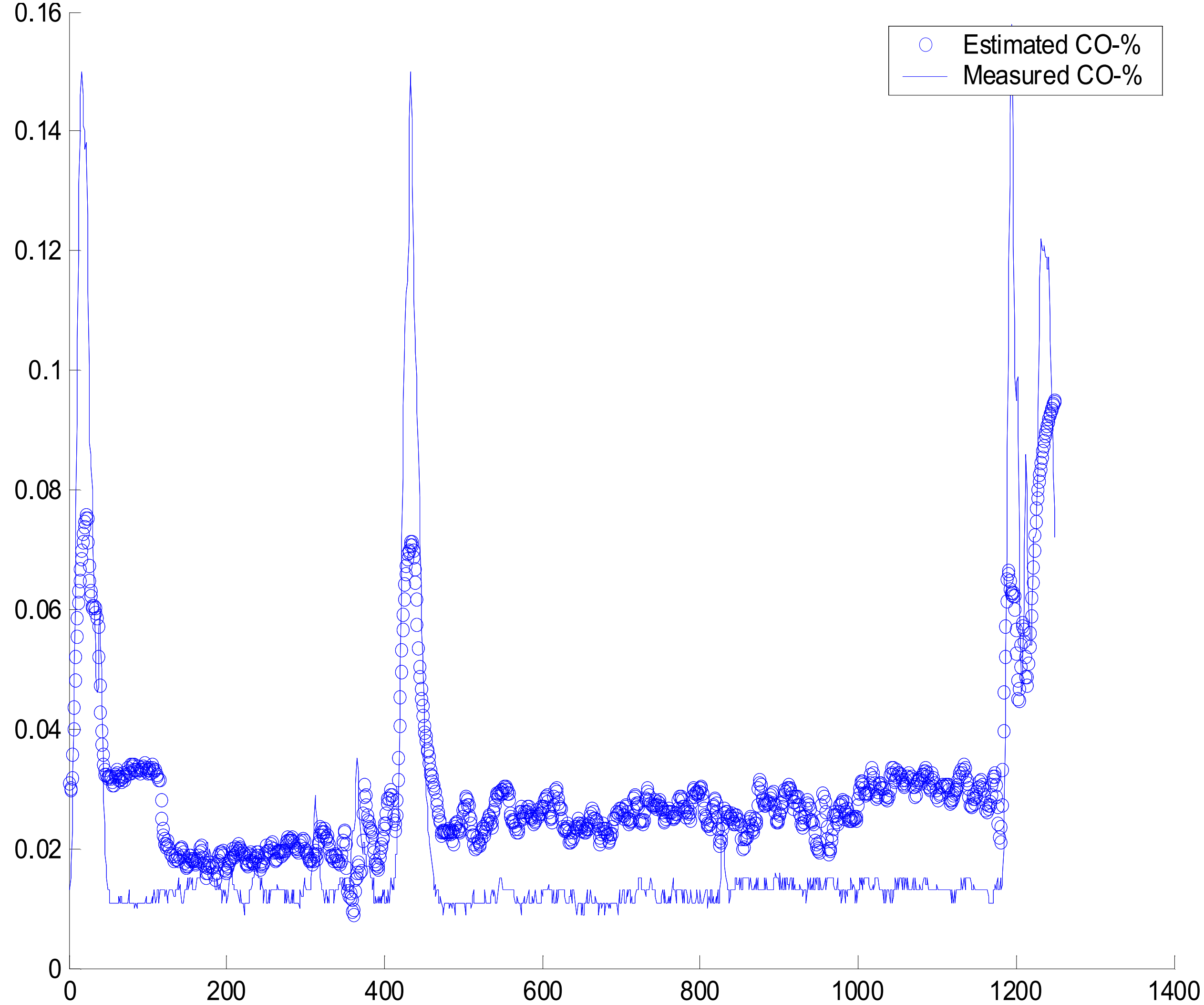
Monitoring of flue gas O2 vol.-%

Case: a 300 kW boiler, fuel: wood chips



CO-monitoring

Case: a 300 kW boiler, fuel: wood chips



Conclusions

- The process was identified using design of experiments
  - CO emissions can be controlled with primary/secondary air ratio and total air feed
  - Heat output can be controlled with fuel power
  - Total air feed and fuel power control the CO_2/O_2 concentrations in flue gas
- Step response test results
  - Local behaviour of process variables can be modelled with 1st order transfer functions
  - Separate models have to be created for different operating points
- The usability soft sensors in monitoring and control of the process was studied
  - CO_2/O_2 can be modelled using temperature measurements
  - CO model needs more research

THANK YOU FOR YOUR ATTENTION!!

- Kai Pietilä, VTT Processes, kai.pietila@vtt.fi
- Mika Ruusunen, University of Oulu, mika.ruusunen@oulu.fi

Annex 5. A novel electrostatic precipitator (ESP) for residential combustion

Morten Berndtsen, the National Institute of Technology, Environment and Safety, Oslo, Norway

End-of-pipe solution for removing respirable particles - from combustion of solid fuels in domestic households

By Arne Thomas Haaland
Applied Plasma Physics ASA

Nordic Bioenergy Conference
25-27 October 2005, Trondheim

History…..

- APP was founded in 1997 to exploit the potential in the use of non-thermal plasma for air pollution control applications
- Through commercial deliveries of industrial scale odour abatement and particulate removal systems, a considerable experience is gained
- The idea of developing a unit applying the non-thermal plasma technology in an end-of-pipe unit for domestic household chimneys was initiated in 1997 and has been pursued ever since
- In 2002, a CRAFT project under EU's 5th frame program was initiated under the acronym CleanAir, to further develop this technology towards a commercial prototype

CLEANAIR – Project
Project information

- Project acronym: CleanAir
- CONTRACT NO: EVK4-CT-2001-30005
- Project Period: 1st May 2002 – 31st April 2004
- Total project: Euro 1.264.908
- Financed under the EESD programme
- Industrial partners; APP (Norway, Sereps (France), VUKOV (Slovakia), CSO (UK), ShroederPlast (Denmark), BK+K (Germany) (in reality Erlus AG)
- RTD partners: TI (Norway), PERA (UK)

Background information

- urban air quality

Ambient air quality – some facts

- **WHO Working Group – Bonn, Germany 13-15 January 2003: "Health Aspects of Air Pollution with Particulate Matter, Ozone and Nitrogen Dioxide" – recommendations with regards to PM:**
  - **fine particles ($PM_{2,5}$) are strongly associated with mortality and hospitalisation for cardio-pulmonary disease – recommendation that air quality guidelines (AQG) for $PM_{2,5}$ is developed.**
  - **Long term exposure to ambient PM concentrations may lead to marked reduction in life expectancy primarily due to increased cardio-pulmonary and lung cancer mortality**
  - **Negative effects are likely in lower respiratory symptoms and reduced lung function in children and chronic obstructive pulmonary disease and reduced lung function in adults**
  - **The Global Burden of Disease project: Exposure to fine particles in outdoor air leads to about 100.000 deaths representing 725.000 years of lost life in Europe annually.**

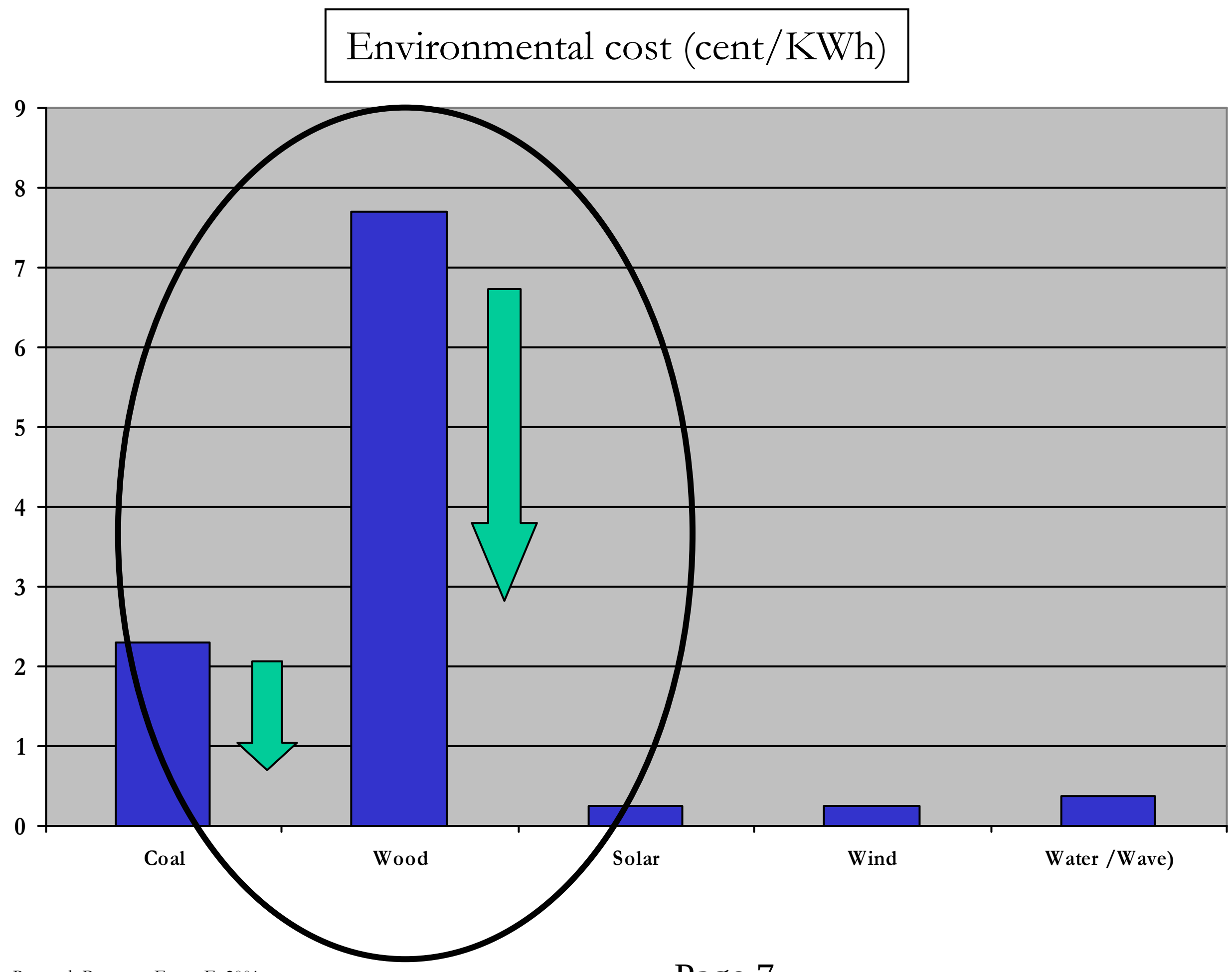
Ambient air quality – EU regulations

- **1996 Framework Directive and daughter Directives.**
- **Revision of directive regarding limit values for ambient PM concentrations:**
  - **Based on new information with regards to health effects**
  - **$PM_{2,5}$ is more potent than larger particles and are strongly associated with increased mortality and cardiovascular and lung disease**
  - **PM from combustion engines, burning of oil and coal and wood burning are especially harmful**
- **Recommendations:**
  - **Use $PM_{2,5}$ as main air quality indicator for PM in ambient air and replace limit values for PM10 in 2005**
  - **Possible limit values for $PM_{2,5}$:**
    - **Long-term exposure: 12 – 20 μg/m3**
    - **Short-term exposure: 35 μg/m3 (and 35 exceedings per year)**
  - **Postpone deadline for attainment of 24 hour limit value for 2005**

Actions are implemented with regards to industrial sources and traffic => making emissions from domestic heating with solid fuels a more dominating source

Our driving motivation:

To make burning of solid fuels like wood and coal to a sustainable, environmental friendly and competitive renewable energy source.



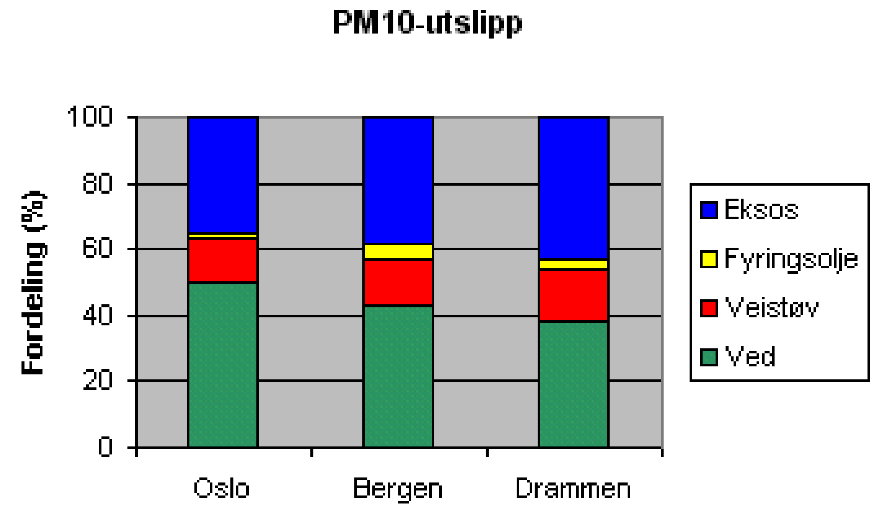
92% of the environmental costs for burning wood originates from respirable dust emissions.

Source : European Research Program, ExternE, 2001
"New renewable energy sources", Kanenergi, 2001

A major part of respirable dust in many urban areas derives from combustion of solid fuels

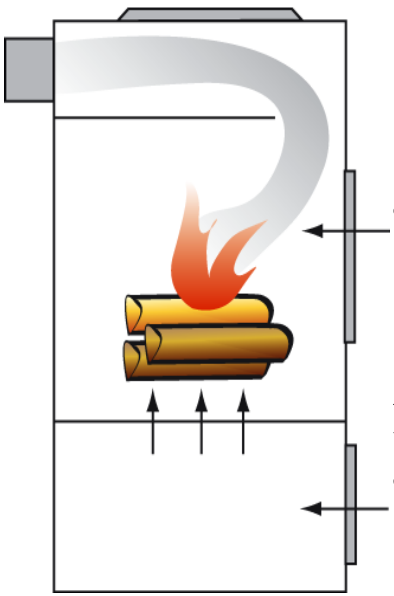
- Burning of wood in private households i Norway contributed to 61% of the total respirable dust emission in 1999.
- Locally as high as 90 % during winter season

Source: Utslipp til luft fra vedfyring i Norge – SSB 2001/36



A report from the Danish National Environmental Research Institute issued in 2005, documents that 47% of the total dust emissions in Denmark has its origin from burning of wood in private households!

Characterisation of emission: Three different combustion phases

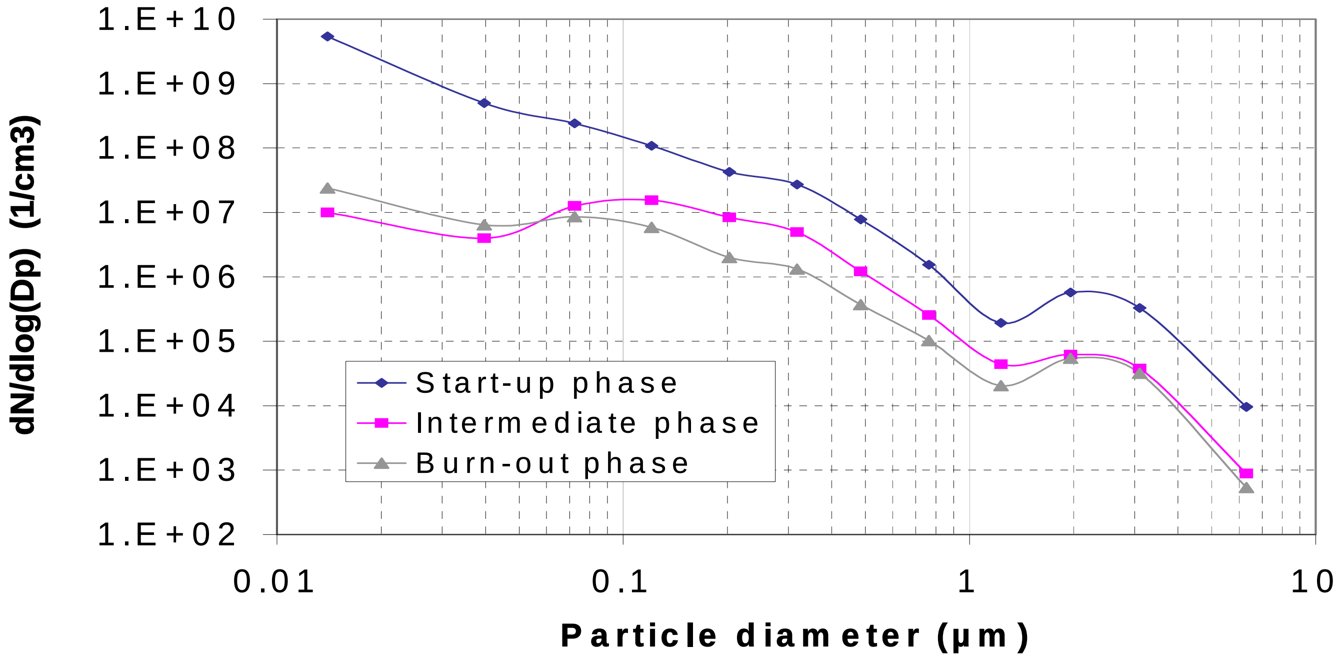


Phases	Particles (mg/dry Nm³)		Particles (1/cm³)	
	Wood	Coal	Wood	Coal
1. Start up	126	26	3.50E+09	3.39E+08
2. Inter-mediate	36	22	1.65E+07	2.49E+07
3. Burn out	4,6	1,7	2.04E+07	3.67E+07
Whole period			2.03E+09	2.07E+08

The start-up phase is a significant contributor to the total particle emission during a complete combustion cycle

APP

Characterisation of emission from fuel combustion
Burning of wood

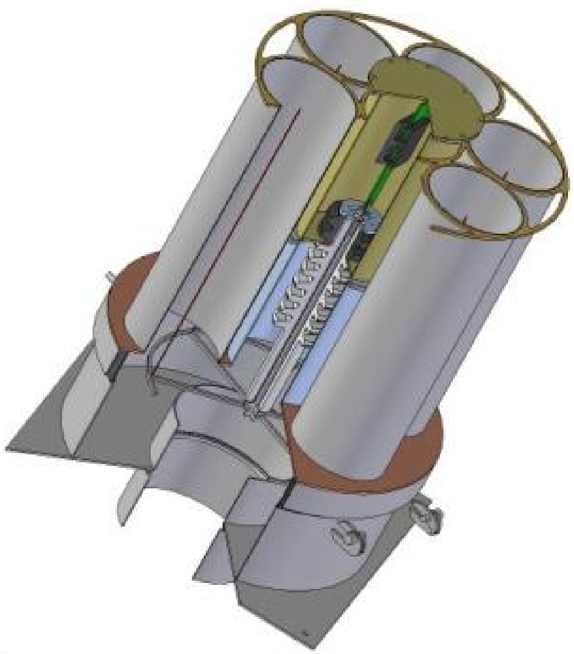


Important: Small scale combustions of wood do create small (< 2,5 µm) and very small (< 0,1 µm) particles => especially harmful particles

CLEANAIR – Prototype
Industrial objectives achieved

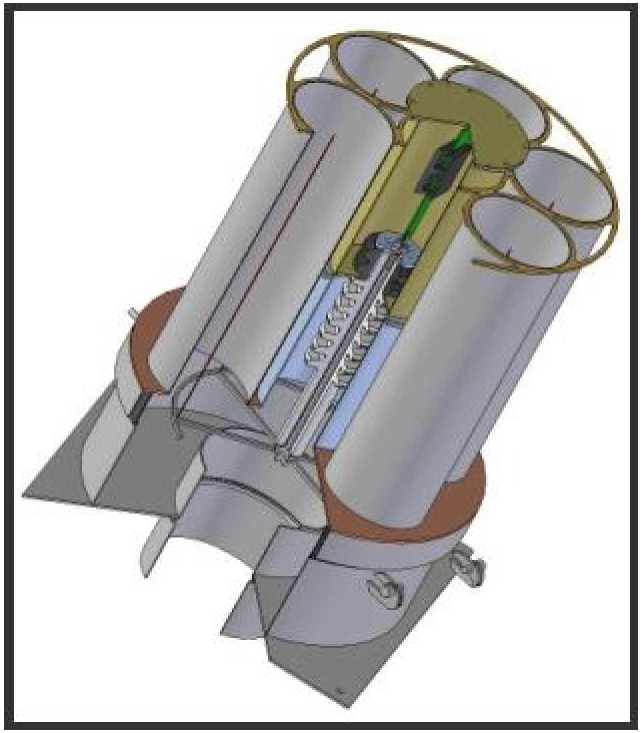
- ✓ Cleaning efficiency better than expected: Cleans emissions from burning of solid fuels with an efficiency of 90-95 % => significantly lower emission than alternative solutions in all burning patterns
- ✓ Maintains the chimney functions: no reduction in draft
- ✓ Sales price target of 400 € is achievable (even lower in larger series) => very cost competitive compared to alternative technologies
- ✓ Electric power consumption verified to stay well within 120 W with full cleaning efficiency.

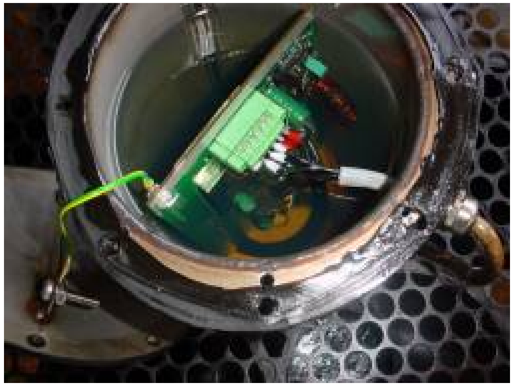
CLEANAIR – Prototype
Industrial objectives achieved



- ✓ Size and weight acceptable for end of pipe installation – demonstrated in field tests
- ✓ Unit designed to collect up to 20 kg of deposit material. Field test confirm ability to maintain operation for more than 1 year without attendance
- ✓ Advanced automation functions implemented enabling unit to automatically start and stop on request (when fireplace is in use). No user interaction is required in normal operation
- ✓ Safety parameters addressed, including electromagnetic fields, noise etc.

The CleanAir unit





Testing of the CleanAir unit

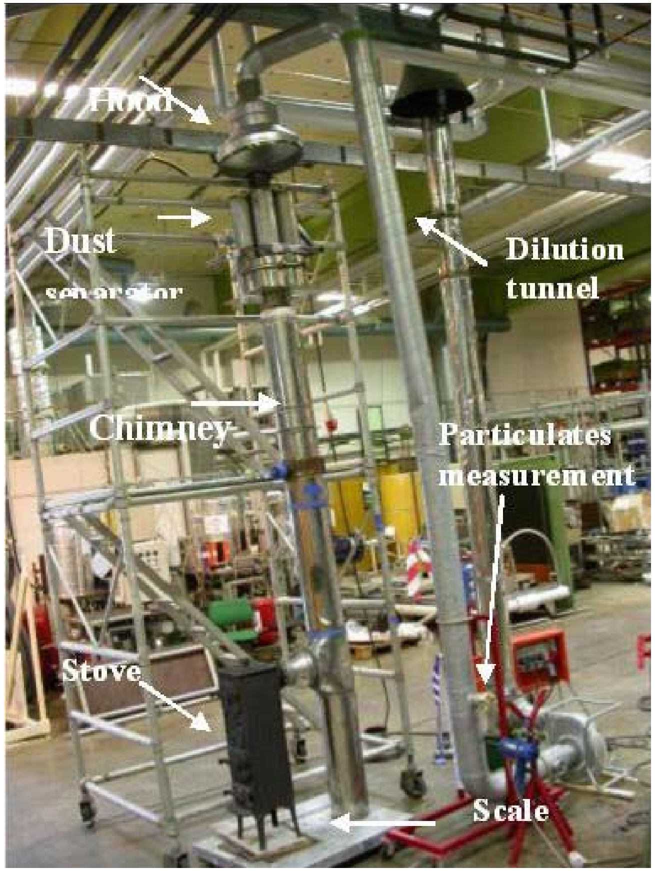
- Field tests done under realistic conditions in Norway
- Laboratory testing done at Statens Provningsanstalt in Sweeden

Field verification:

- Tested in a domestic household in Norway
- Fireplace intensively used during test period. Fuel consumption equivalent to more than 1 year.
- Test proved successful and gave valuable input to final industrialization of unit.

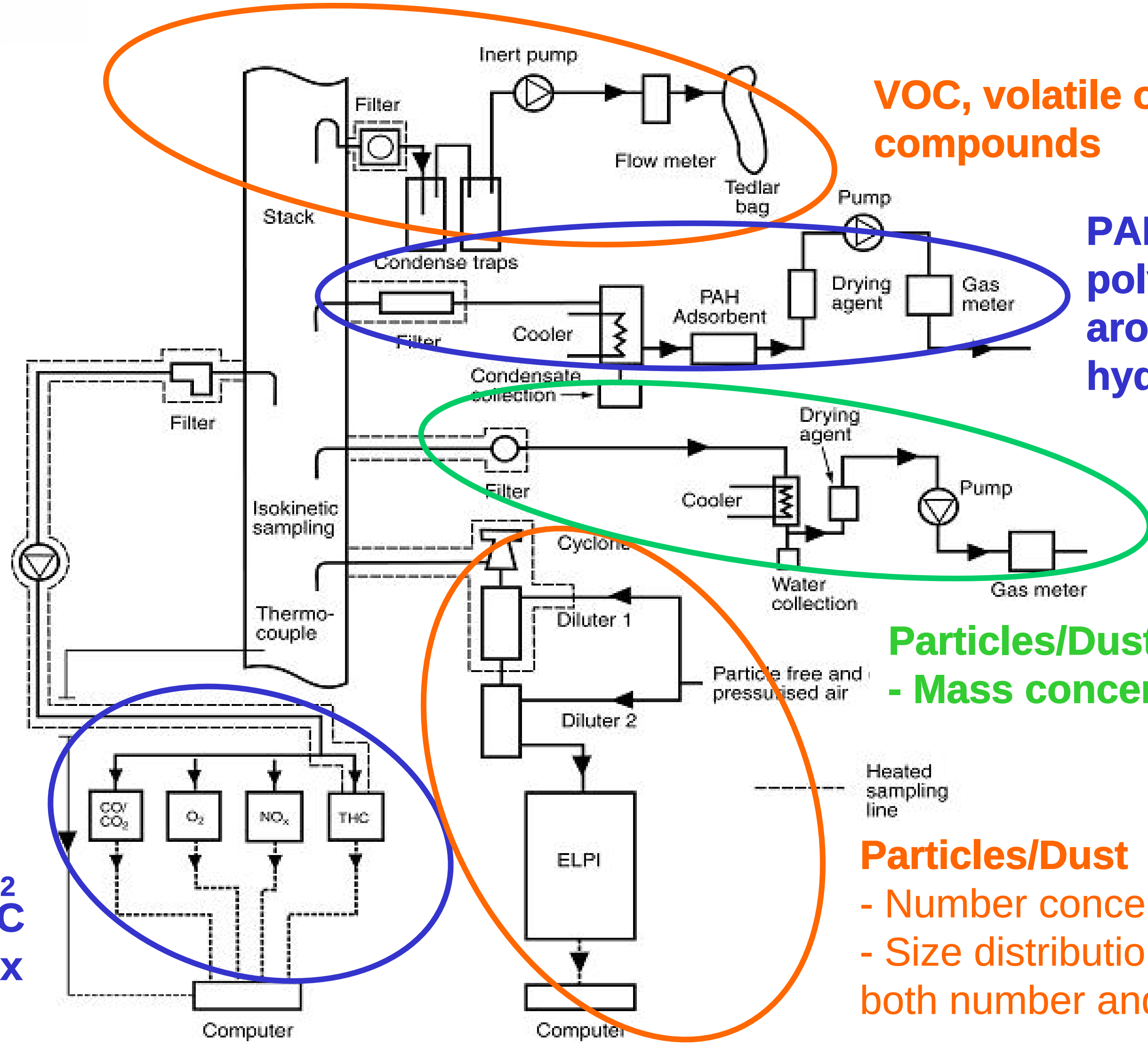
Laboratory test of prototype

- Extensive laboratory testing done to establish unit efficiency
  - Prototype connected to old type fireplace without secondary combustion
  - Tested both on coal and wood
  - Tested under varying ambient conditions
- Comparing tests done to establish efficiency compared to modern clean burning technologies



Test set-up

Measurement techniques used in Lab



VOC, volatile organic compounds

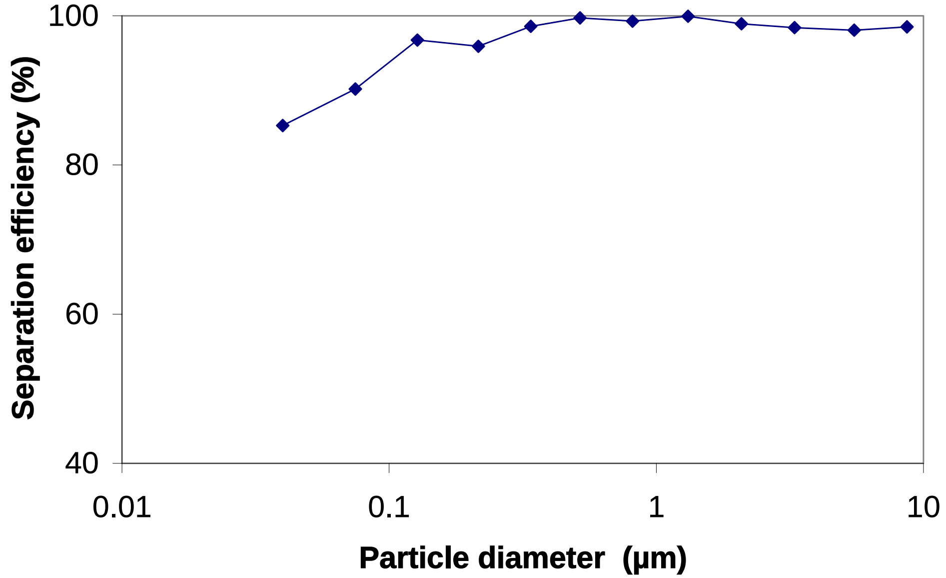
PAH, polycyclic aromatic hydrocarbons

Particles/Dust
- Mass concentration

Particles/Dust
- Number concentration
- Size distributions, both number and mass

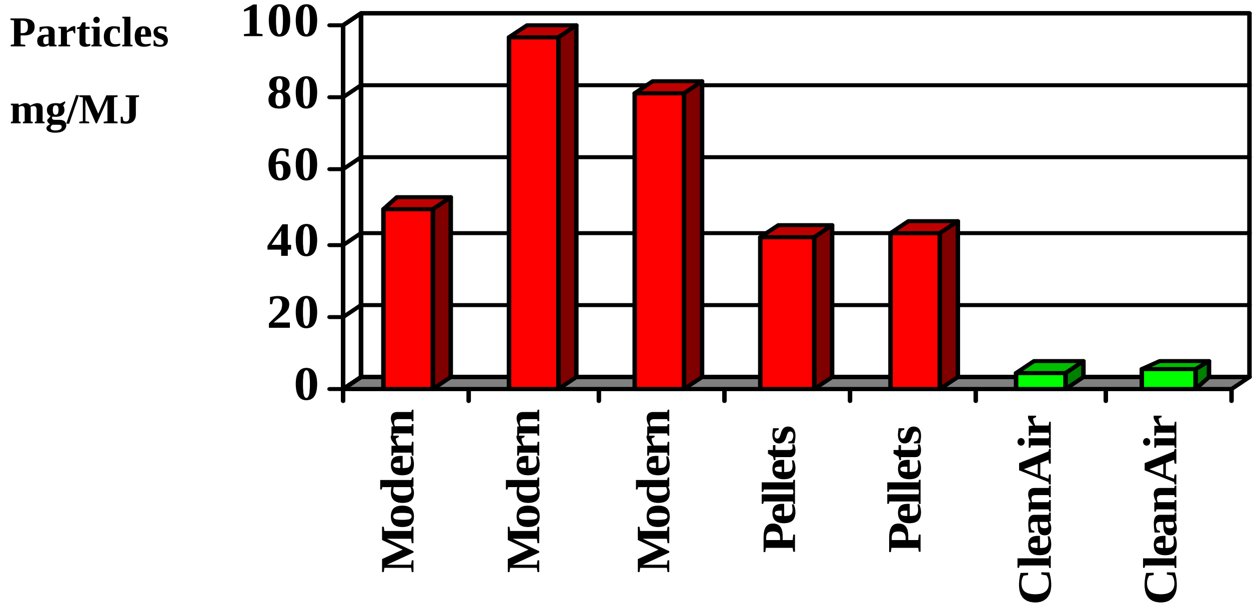
O_2
CO
CO_2
TOC
NOx

CLEANAIR –
Particle cleaning efficiency



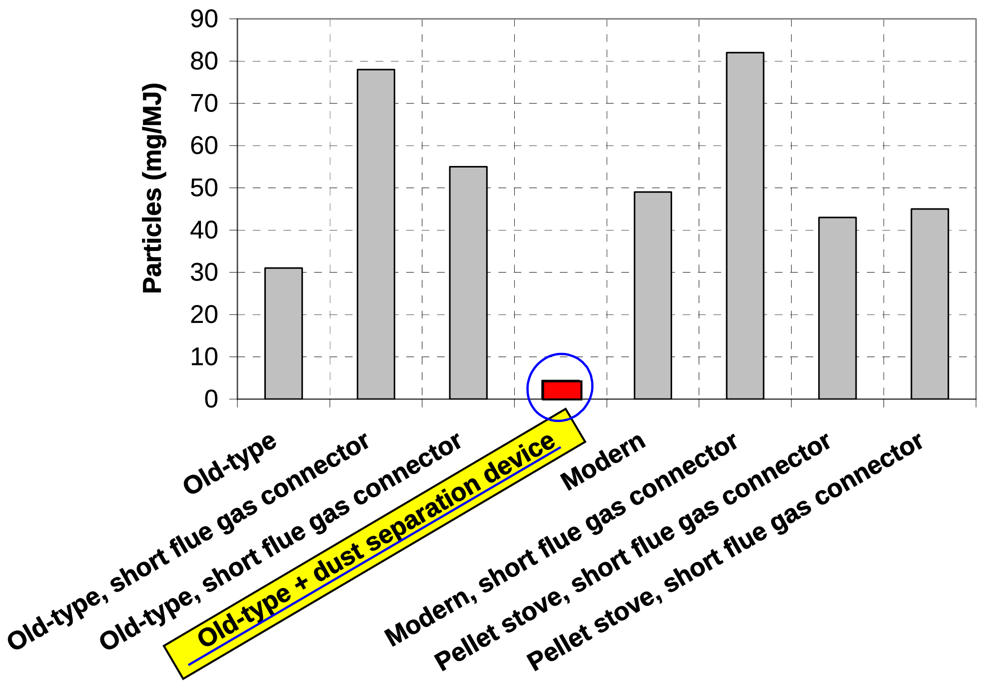
The CleanAir technology represents efficient cleaning for all relevant particle sizes

CLEANAIR –
Comparative studies between alternative technologies



Note that the comparison above compensates for the improved utilization of fuel in modern clean burning fireplaces.

Clean burning fireplaces is claimed to be the optimum solution to reduce PM_{10} emissions from burning of solid fuels -



- Our research indicate that this is an unwise approach to this challenge…….

Case study: The City of Oslo

Oslo inner city

- In the City of Oslo, 75.000 fireplaces emits 400 tons of PM_{10} pr. year. Of these, 17.000 fireplaces are located in the inner city, emitting 90 tons pr. year.
- The health effect and associated society costs for PM_{10} is calculated to be NOK 1.950 pr. kg * which implies a total cost for the City of Oslo of 780 MNOK pr. year
- For Oslo inner city, the cost is 176 MNOK

* Source: *Helseeffekter og samfunnsøkonomiske kostnader av luftforurensning",* Rosendahl 2000

Case study: The City of Oslo
Implementing the CleanAir technology gives significant payback

- Installation of 17.000 CleanAir units in Oslo inner city (100% coverage) will result in a reduction of PM_{10} emission by 90%.
- Total investments
  - Unit cost assumed to be 3.000 NOK each
  - Installation cost assumed to be 1.500 NOK each
  - Total investment for 17.000 units adds up to 76,5 MNOK
- Total reduction in environmental costs pr. year:
  - 90 tons PM_{10} – 81tons PM10 = 9 tons remaining PM_{10} emission
  - 176 $MNOK_{uncleaned}$ – 17,5 $MNOK_{remaining}$ = 158,5 MNOK cost reduction

$\Rightarrow$ **Payback of investment in less than one year!**

Positive conclusions ☺

- Burning of solid fuels in domestic households becomes an increasingly important energy source with increasing electricity and oil/gas prices.
- Emissions from burning of solid fuels gains significance as the main source of respirable dust pollution in many urban areas throughout Europe (and outside)
- By installing the CleanAir technology, the environmental costs for burning solid fuels may be cost efficiently reduced down to levels comparable with other environmental friendly renewable energy sources like solar, wind and hydro power.
- Case studies show that implementation of the CleanAir technology in urban areas is highly profitable for the society!

However….. ☹

- **The market for air pollution control technology for domestic heating with solid fuels, is closely dependant on local policy decision making**
- **Even if**
  - **authorities in most European countries have today implemented legislations for urban air quality enabling actions for air pollution control requirements in domestic households, and**
  - **possible political measures to enforce these legislations could be specific requirements on allowable emission values, or economic stimulation for environmental friendly solutions,**
- **So far, no such political measures are taken to enforce already approved legislations!**
- **The CleanAir technology seems to be ahead of its time…..**

Final remarks

- The CleanAir technology makes burning of solid fuels to an environment friendly energy source
- Political commitment to enforce already implemented legislations for urban air quality is needed
  - to achieve real environmental improvements
  - to create a market for environmental technology
- Today's policies prevents innovation and creation of new industries and jobs

Thank you for the attention!!

Annex 6. Conclusions and closing

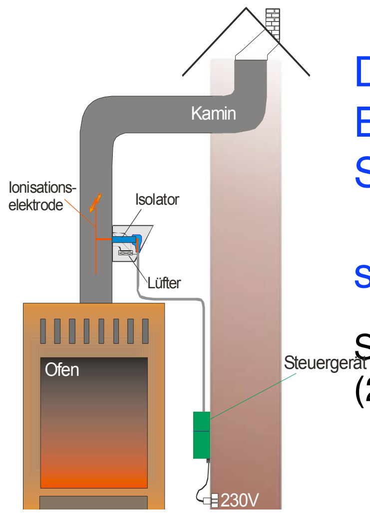
PD Dr. Thomas Nussbaumer, Verenum, Switzerland

Recent Developments in Small Scale Combustion (SSC) Devices

Conclusions
IEA Workshop, Paris 21.10.05

PD Dr. Thomas Nussbaumer
Verenum
8006 Zürich, Switzerland
www.verenum.ch

Electrostatic Precipitator ESP for residential wood combustion



Development in Switzerland by EMPA (Swiss Federal Institute of Material Sciences and Technology)

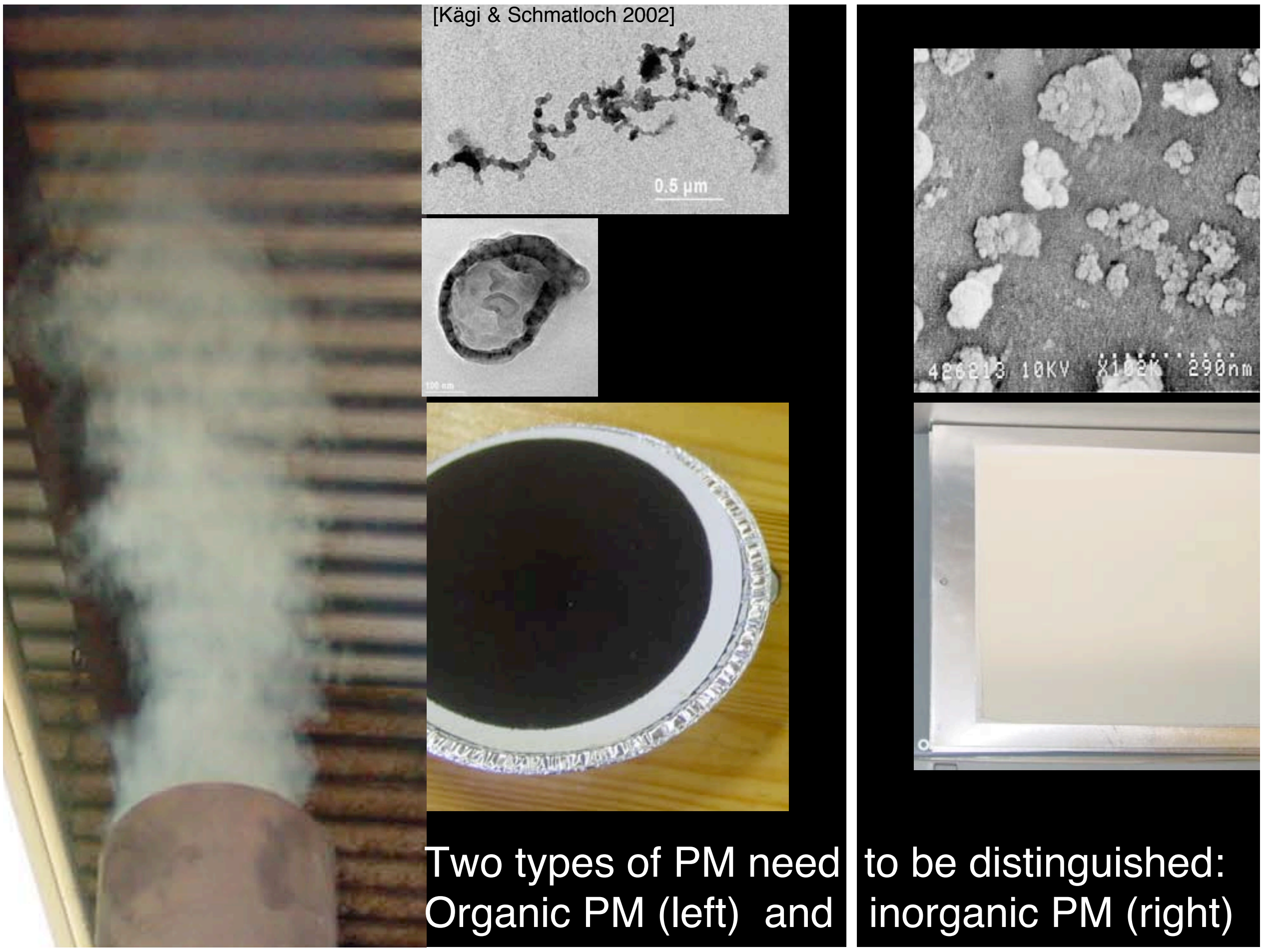
see: www.minipab.ch

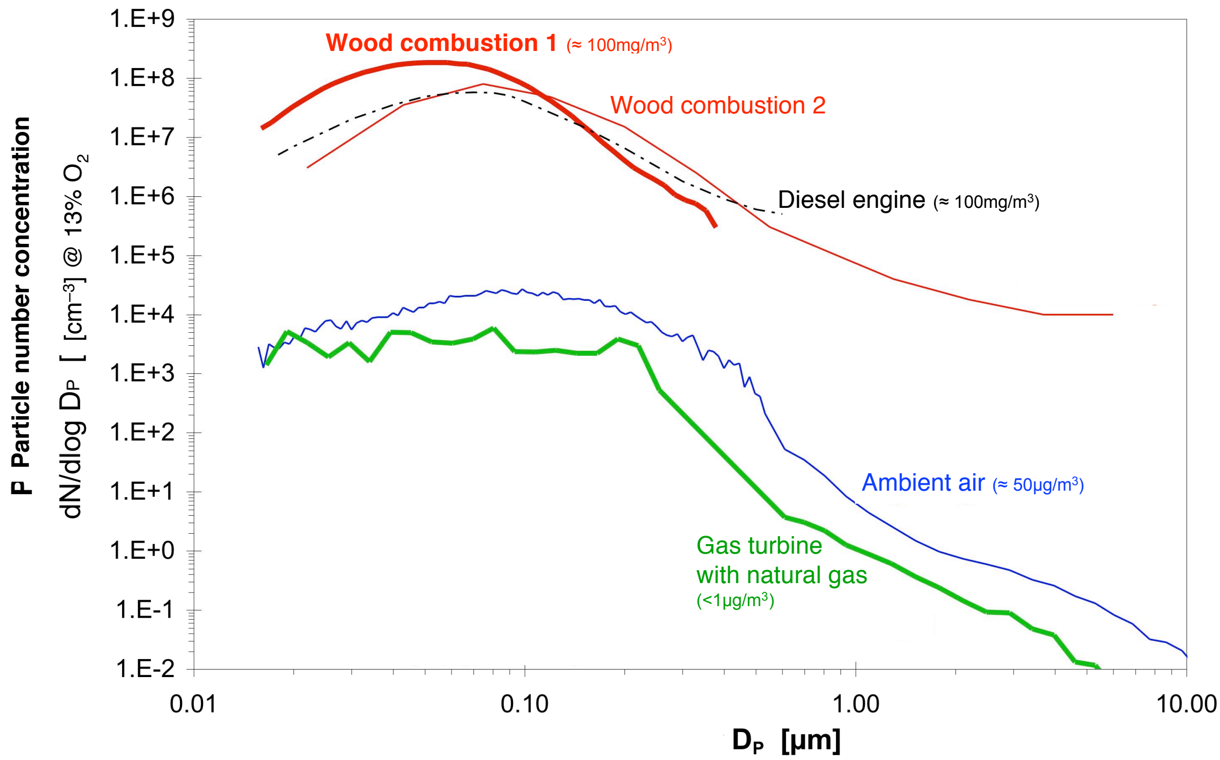
Schmatloch, V., Rauch, S.: Journal of Electrostatics (2005) Vol. 63(2), 85–100

Status of SSC Today

1. Small Scale Combustion is important today for two reasons:
   It has a high contribution
   a) to the global energy demand but
   b) also to the air pollution, mainly PM

2. Small Scale Combustion is increasing





Gas turbine & ambient (Baden, CH): [Klippel et al. 2003] SMPS und OPC
Wood 1 & Diesel: [Oser et al. 2000] & [Schmatloch 2000] with SMPS
Wood 2: [Johansson 2002] with ELPI transformed to Stokes D

Verenum

Where are we going ?

2 Examples of new developments:

Verenum

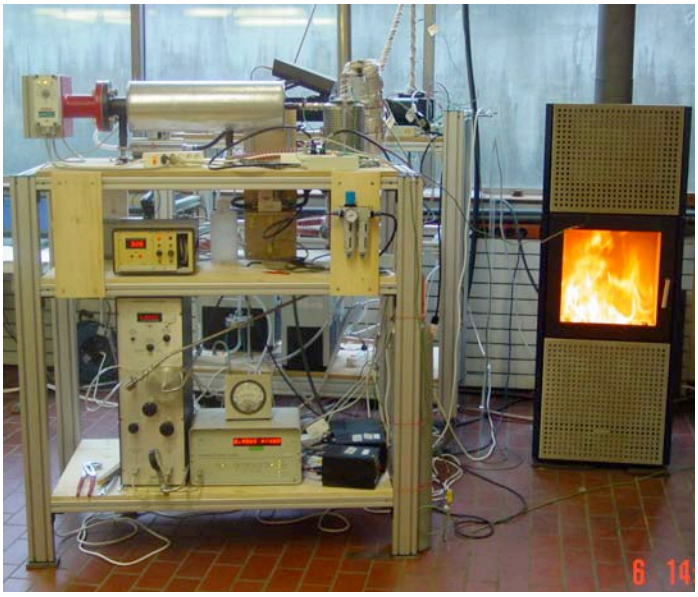
Example 1:   1-stage combustion with flame quenching ....


NZZ am Sonntag • 24. Oktober 2004

Auf kleiner Flamme: Im Dutchtub lässt es sich mit oder ohne Bier gut auch bei herbstlichen Aussentemperaturen aushalten.

Der Kannibalenkochtopf

Example 2: 2-stage combustion for log wood is possible !



Premixed gas flame

Equipment for analysis of analysis of particle size distribution from 15 nm to 40 microns by Verenum (SMPS and OPC)

Prototype stove with two-stage combustion achieving < 50 mg/m3 during start-up and < 15 mg/m3 during stationary period, TIBA Holzfeuerungen AG Bubendorf (Switzerland)

Conclusions (1)

1. Relevant improvements have been achieved during the past 10 years:
   – Control systems
   – Pellet combustion
   – Particle removal
   ...

2. Good combustion systems with high efficiency and low emissions are available

Verenum

Conclusions (2)

BUT:

1. Hugh differences
   between technologies and countries

2. a) Log wood is under estimated
   b) Log wood is more difficult (batch !)

   gap between developmtents and relevance

Verenum

Where should we go ?

Outlook/Target for SSC:

–> Implementation of SSC

1. To increase biomass share as energy source by additional SSC
2. To replace existing low quality systems by improved systems
   (this enables a) a relevant increase of useful energy with the same amount of currently used wood and b) a huge reduction of air pollution)

Outlook/Target for SSC:

–> Implementation of SSC

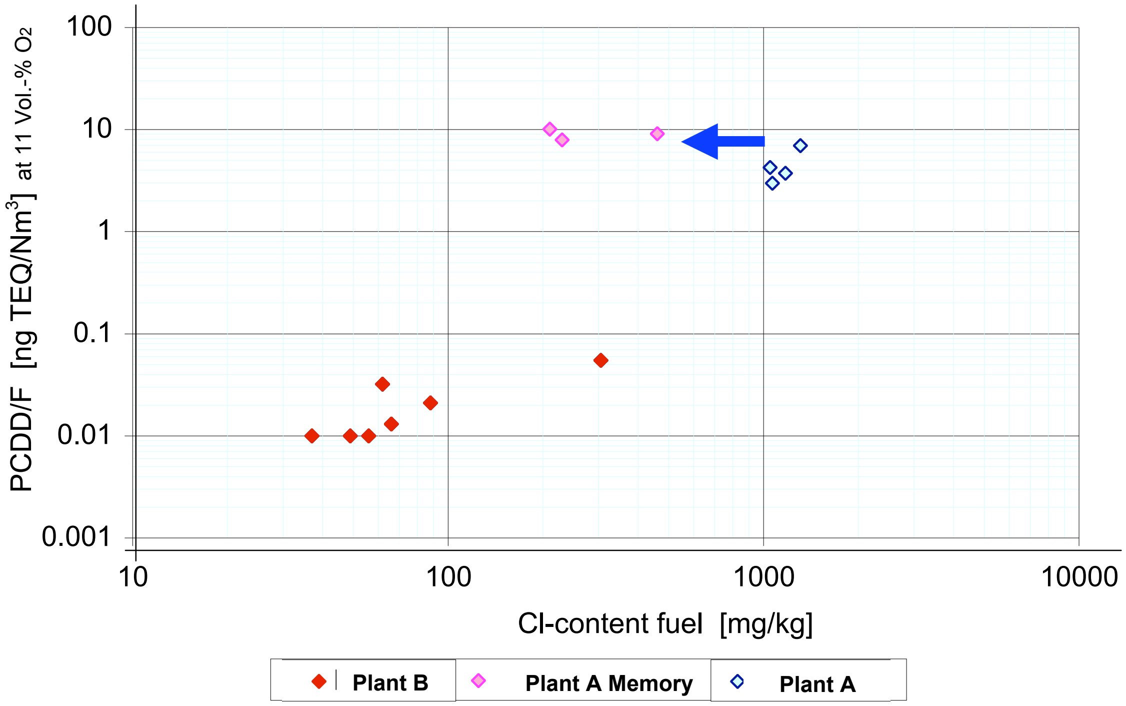
But with high requirements, i.e., ONLY high quality SSC with

1. High quality SSC systems –> Certification test, Quality labels & Quality assurance
2. Correct operation –> Information, technical measures, periodic control (and consequences, i.e., penalty for illegal incineration)

Fuel is very important: Example of hard wood which is dry outside

But wet inside –> w > 25%

Memory-Effect for PCDD/F (Hypothesis)



[Fastenaekels 2003]

Outlook/Target for SSC:

–> Implementation of SSC

But with high requirements, i.e., ONLY high quality SSC with

1. High quality SSC systems –> Certification test, Quality labels & Quality assurance
2. Correct operation –> Information, technical measures, periodic control
3. Optimum fuel –> Fuel standardization