Particle emissions from residential wood combustion – Design and operation conditions determine health impacts

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Particle emissions from small wood furnaces strongly depend on furnace design, operation conditions, and type and properties of the used wood fuel. The aim of the present study is to indicate the range of variability of particle emissions and size distributions and to assess the health impacts of wood particles resulting from different combustion conditions in comparison to Diesel soot. The ability to deal with wood of different quality, which is mainly determined by the water content, is compared for the following combustion devices:

1. A metal stove with small combustion chamber and low mass of ceramics lining,
2. A modern wood stove with large combustion chamber and heavier ceramic lining which fulfils the requirements of the Swiss quality label,
3. A newly designed wood stove with two-stage combustion by gasification and consecutive gas oxidation in a separated combustion chamber with secondary air
4. A modern pellet stove operated with wood pellets and straw pellets.

In addition to conventional mass concentration measurements of solid particles, the time dependence and size distribution of the particle emissions is monitored in the size range from 20 nm to 10 µm by a combination of a scanning mobility particle sizer (SMPS) and an optical particle counter (OPC). Furthermore, the mass concentration of condensable matter is measured and chemical analyses on organic carbon and polycyclic aromatic hydrocarbons (PAH) of solid particles and condensable matter are performed.

The resulting particle emissions vary between 20 mg/m^3 at 13% O_2 for stove no. 3 operated with dry wood, and up to 5 000 mg/m^3 for stove no. 1 operated under very bad conditions. An important finding is that very bad conditions are prevented by the advanced design features of stove no. 3. The size distribution is shifted significantly by operation conditions with a predominant fraction of PM 2.5 in all cases. The spectra for low emissions are comparable to modern oil burners, while bad operation creates a large fraction of particles near 0.5 to 1 µm.

The composition of the particles is an important parameter for the interaction with the human body and resulting health effects. The toxicity of the particles is tested by a standard test method with lung cells of the Chinese hamster. This cell line allows also a standard detection of chromosome defects, which are an indicator for the carcinogenic potential of the applied particles. In a recent study we have shown that particles from automatic wood furnaces are less toxic than Diesel soot [1]. This result is not transferable to small wood furnaces. Unlike automatic furnaces the particles do not mainly consist of salts but contain high concentrations of soot. In addition, condensable organic compounds are found in relevant concentrations. Consequently, the present results show, that wood particles from very bad operation conditions in stove no. 1 exhibit a significantly higher cell toxicity and carcinogenic potential than Diesel soot. Furthermore, the chemical analyses reveal substantially higher concentrations of PAHs, which are assumed to contribute to the increased toxicity.

Reference:

[1] N. Klippel, T. Nussbaumer, K. Meurer, 9th ETH-Conference on Combustion Generated Nanoparticles, 2005.

Acknowledgments:

Swiss Federal Office of Energy (SFOE), Berne; Federal Office for the Environment (FOEN), Berne; Tiba AG, Bubendorf, Switzerland; RCC Cytotest Cell Research GmbH, Rossdorf, Germany; Swiss Federal Institute of Material Testing and Sciences (EMPA), Dübendorf, Switzerland; Alstom Technology Centre, Switzerland; A. Mayer, TTM, Switzerland.

Particle Emissions from Residential Wood Combustion –

Design and Operation Conditions Determine Health Impacts

N. Klippel, T. Nussbaumer, A.Hess, Verenum, Zürich

Focus of this study

- Wood stoves < 20 kW
- Influence of:
  - stove type and design
  - type of fuel:
    - wet and dry wood logs
    - wood and straw pellets
  - operation conditions:
    - small batches of small wood logs or
    - filling of stove with large logs
    - use of air inlet valve
- Quantify particle emissions
- Estimate health impacts based on biological cell tests

Investigated Stoves

Conventional wood stoves

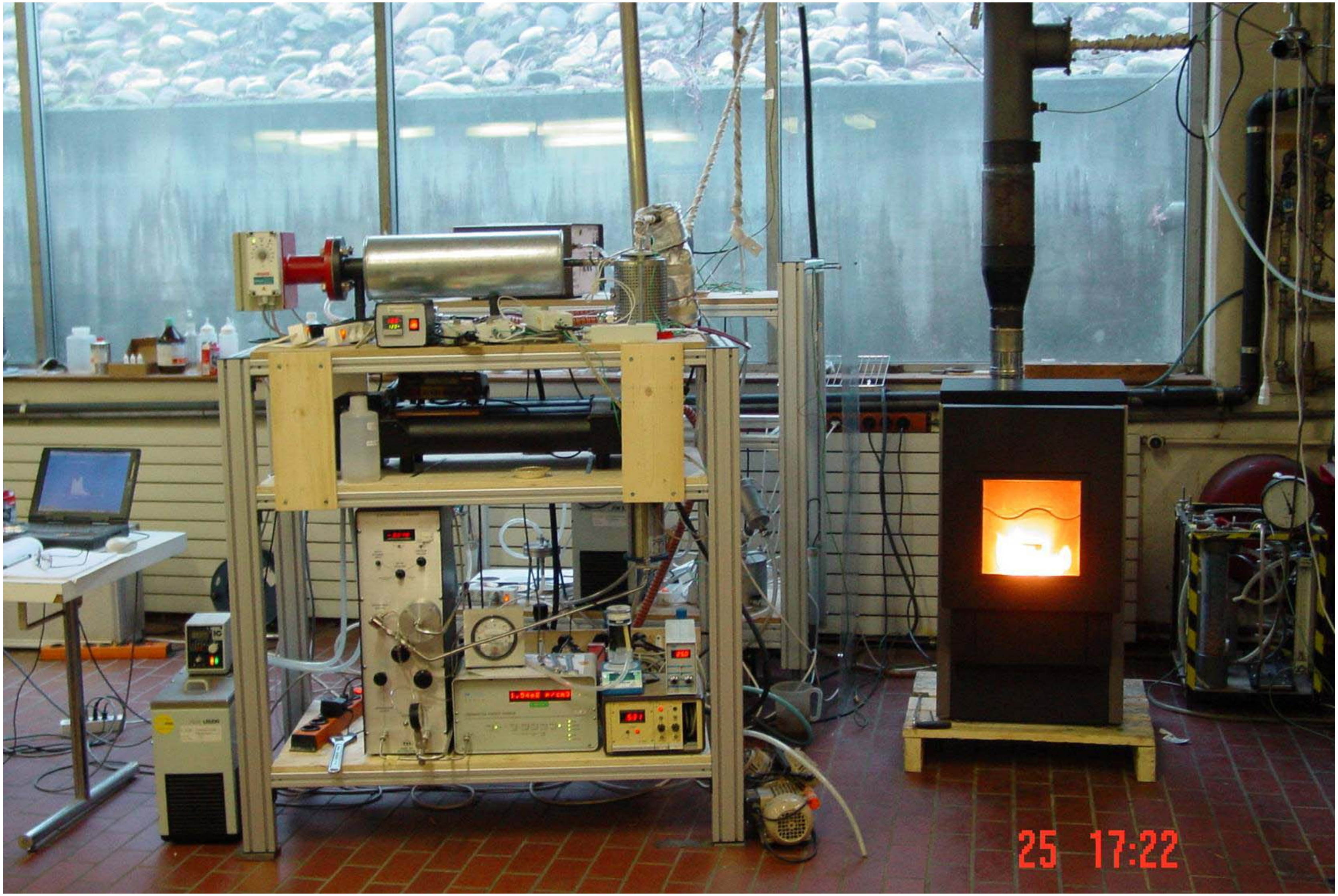
small metal stove (no quality label)

with Swiss quality label for low emissions

Wood stove with two-stage combustion

Pellet stove

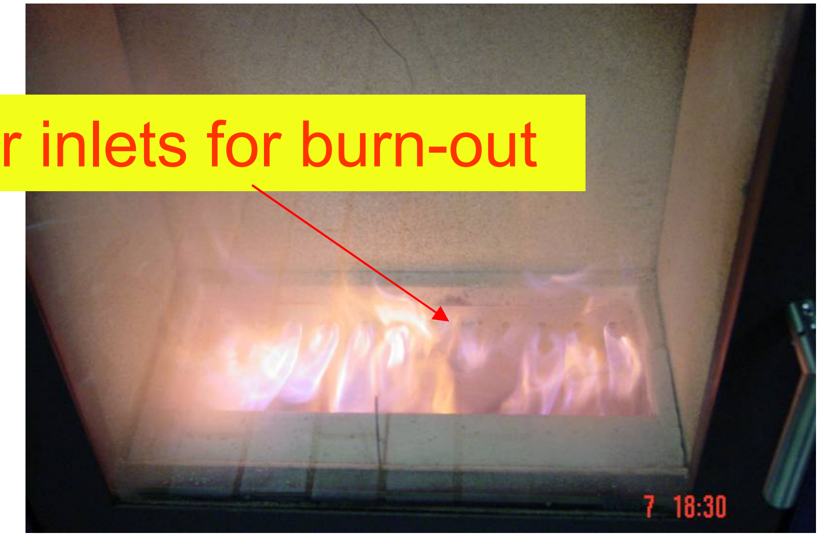
Experimental set-up



Test Methods

- Total particle mass emissions including condensibles according to EPA
- Size distribution from 20nm to 20µm with
  - SMPS
  - Optical particle counter
- Sampling in impinger bottles and on filters
  - for subsequent PAH analysis and
  - biological tests

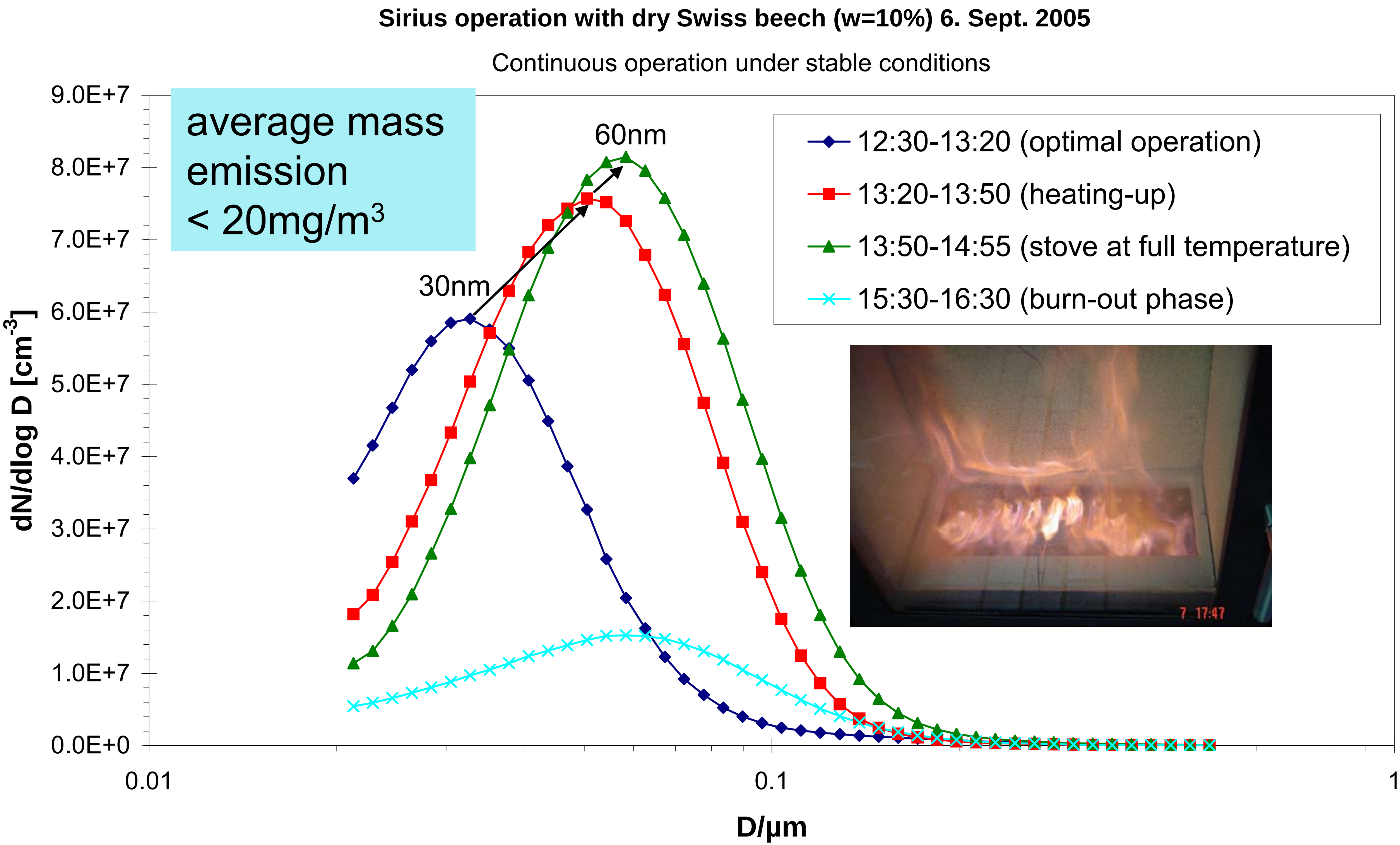
Wood log stove with two-stage combustion



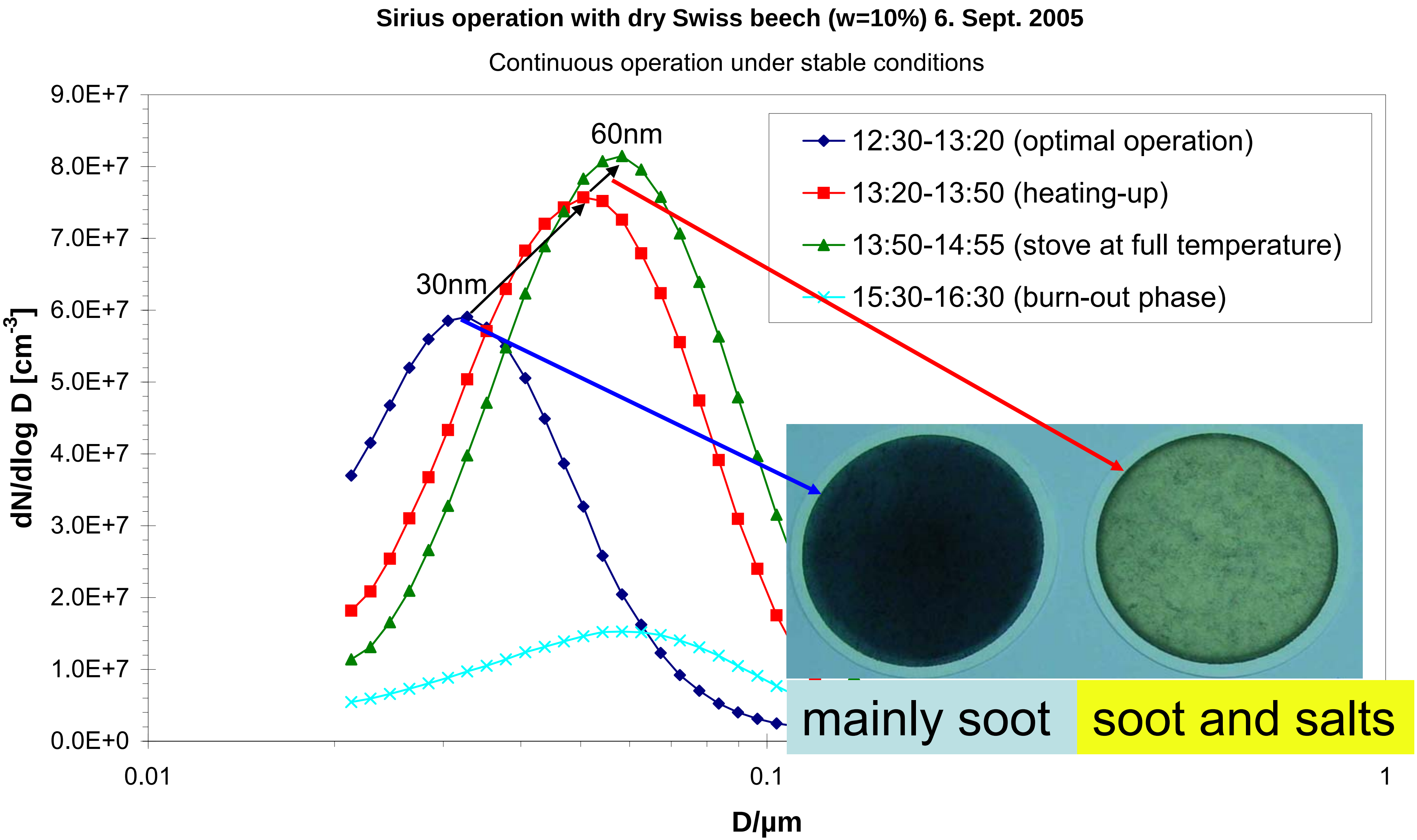
secondary air inlets for burn-out

wood logs in glow bed,
filled from rear side

Two-stage combustion

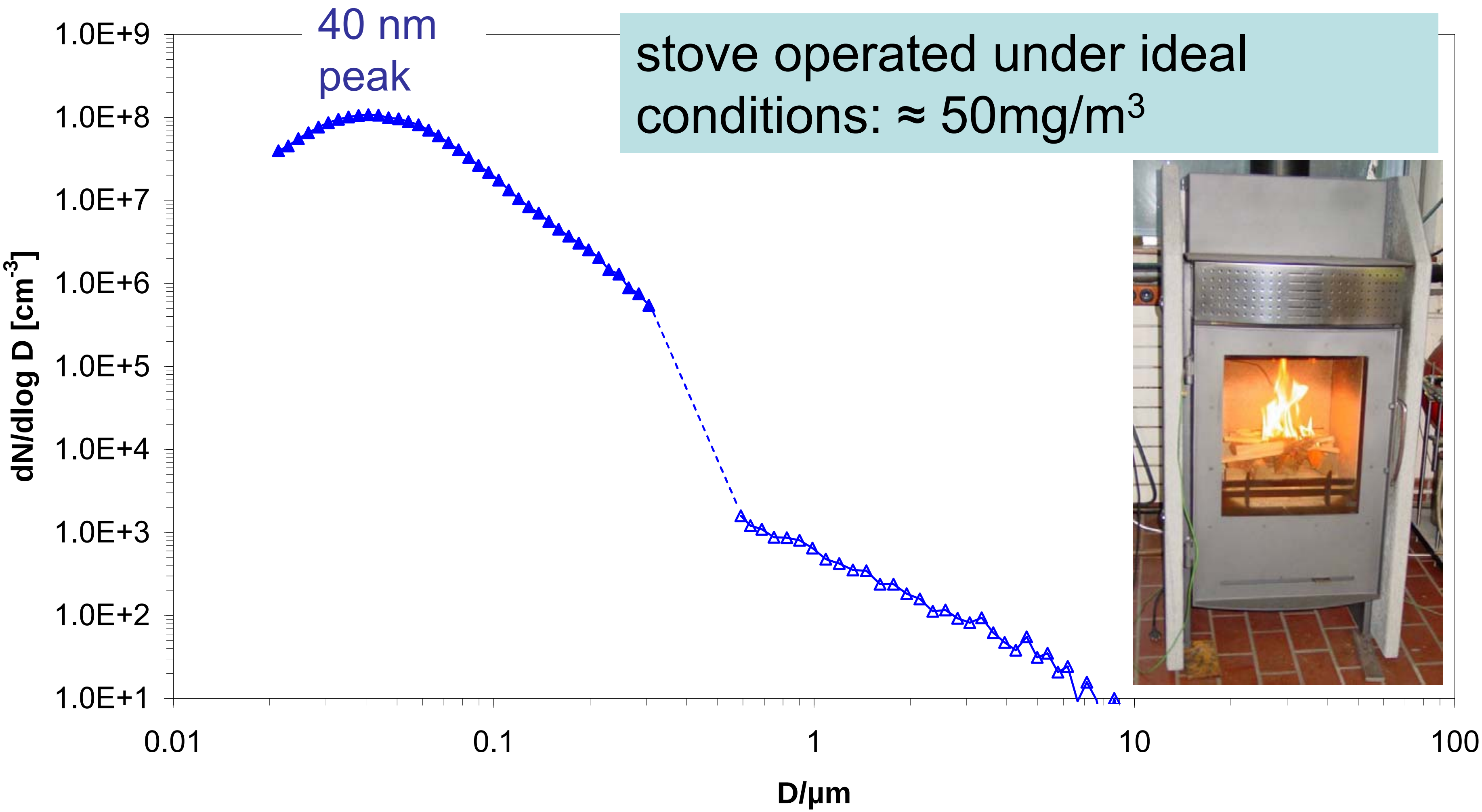


Two-stage combustion

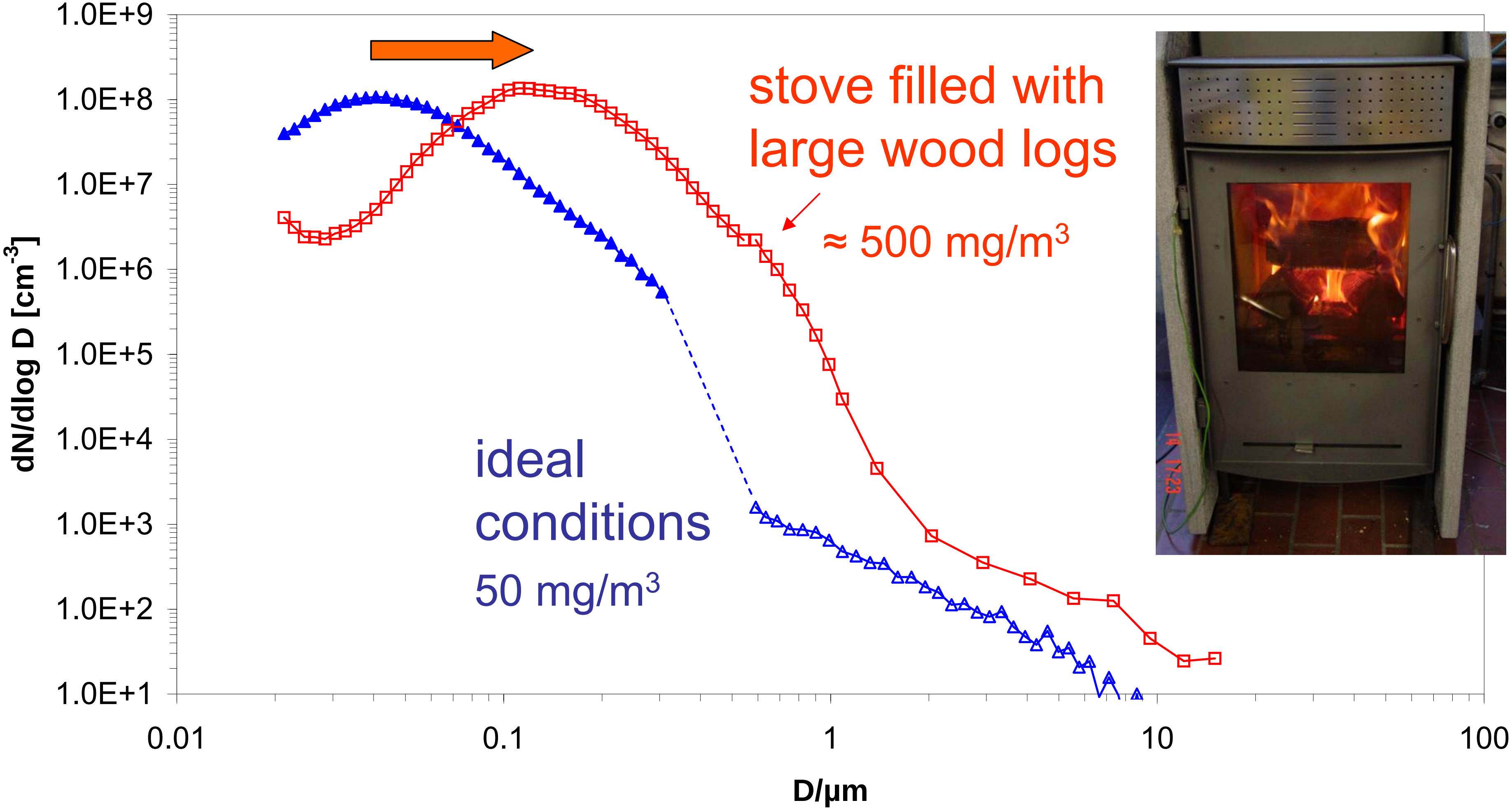


Conventional stove

stove operated under ideal conditions: ≈ 50mg/m^3

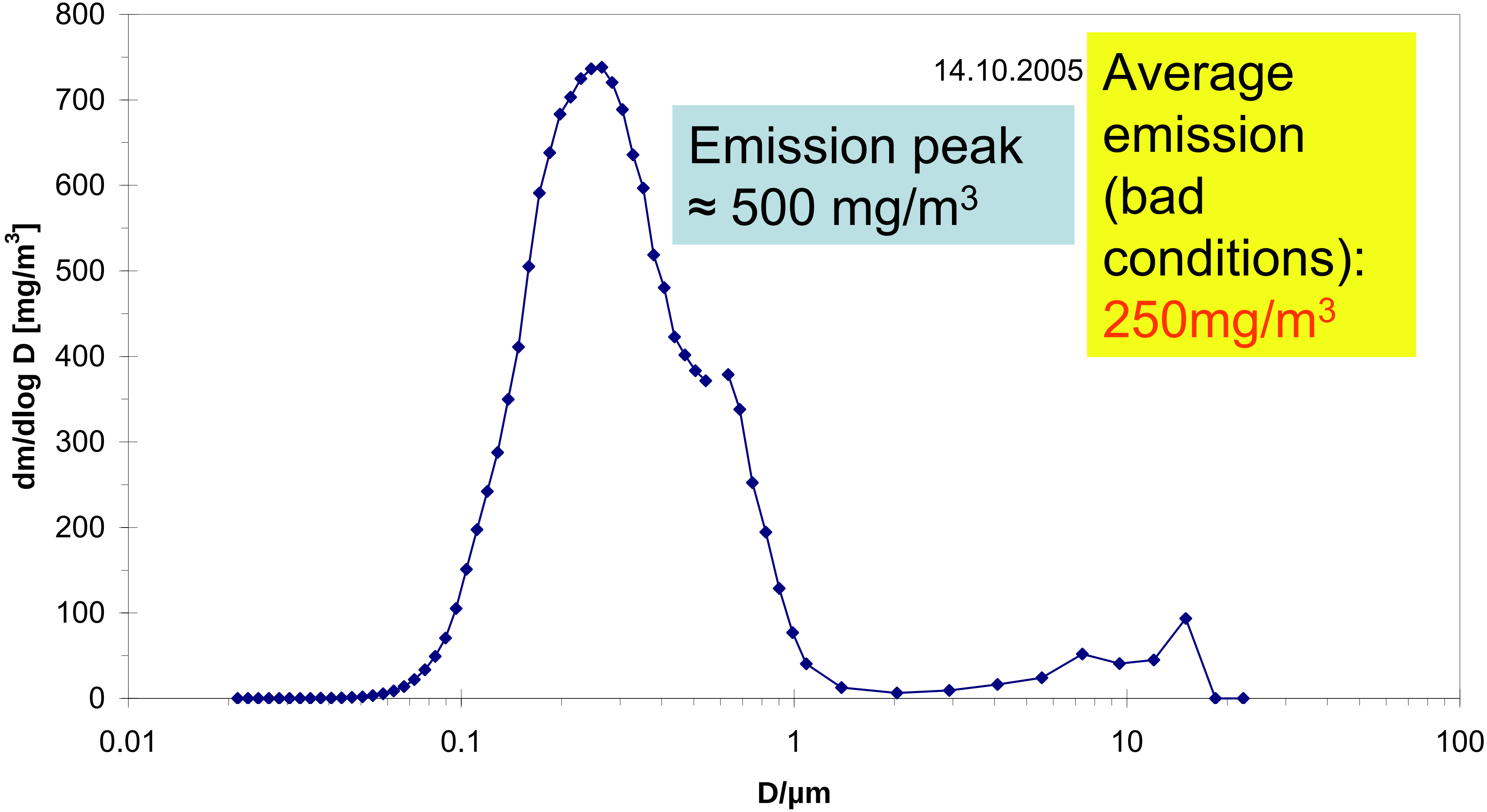


Conventional stove



Mass spectrum, conventional stove

stove filled with large wood logs



Combustion in a small stove

Excerpt of Manual of a small stove

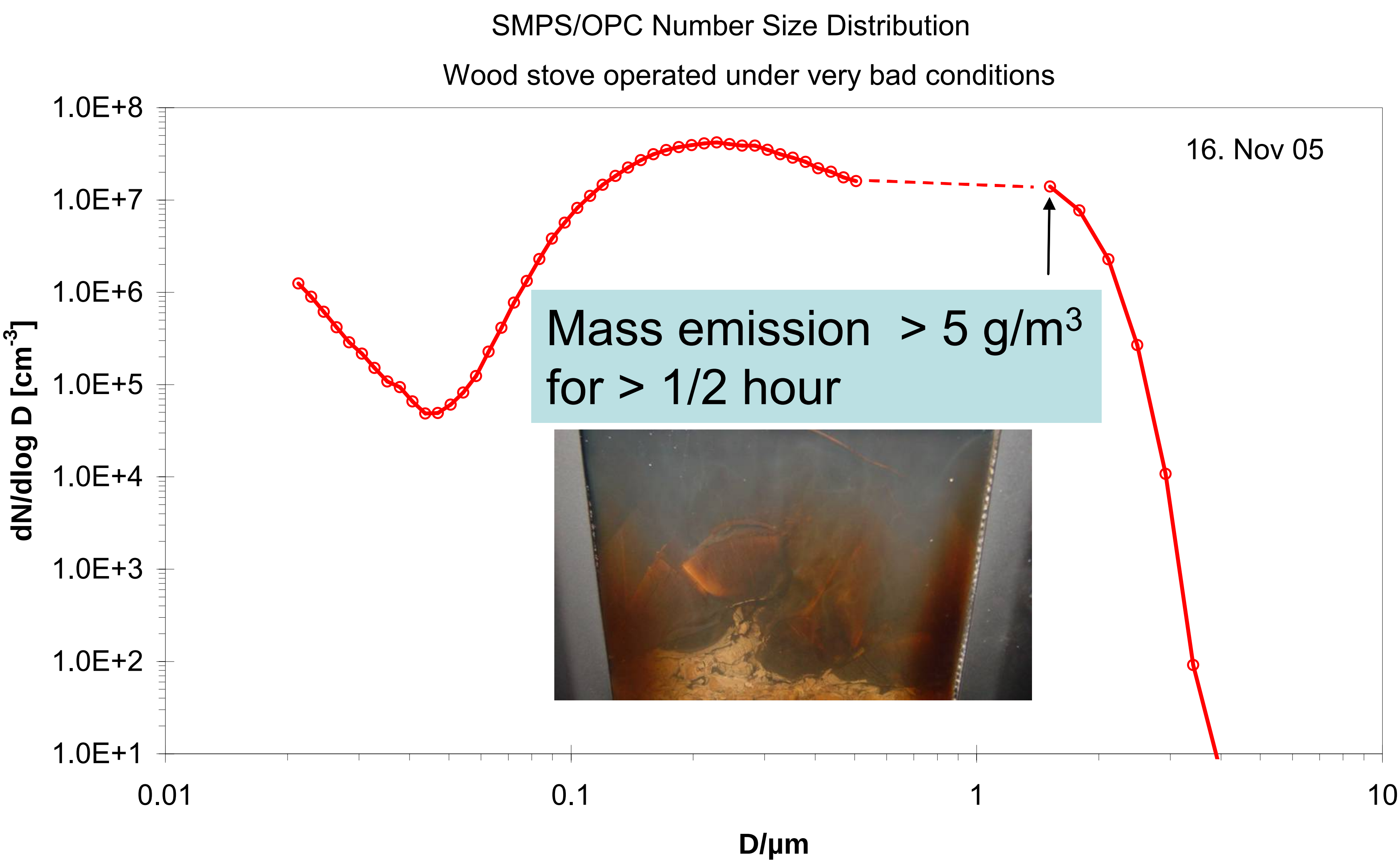
"To reach a good combustion during the whole night, do the following:

(a) establish a glow bed based on the existing fire

(b) fill the stove with wood logs

(c) as soon as the wood starts to burn, close the air inlet"

Incomplete combustion in a small metal stove

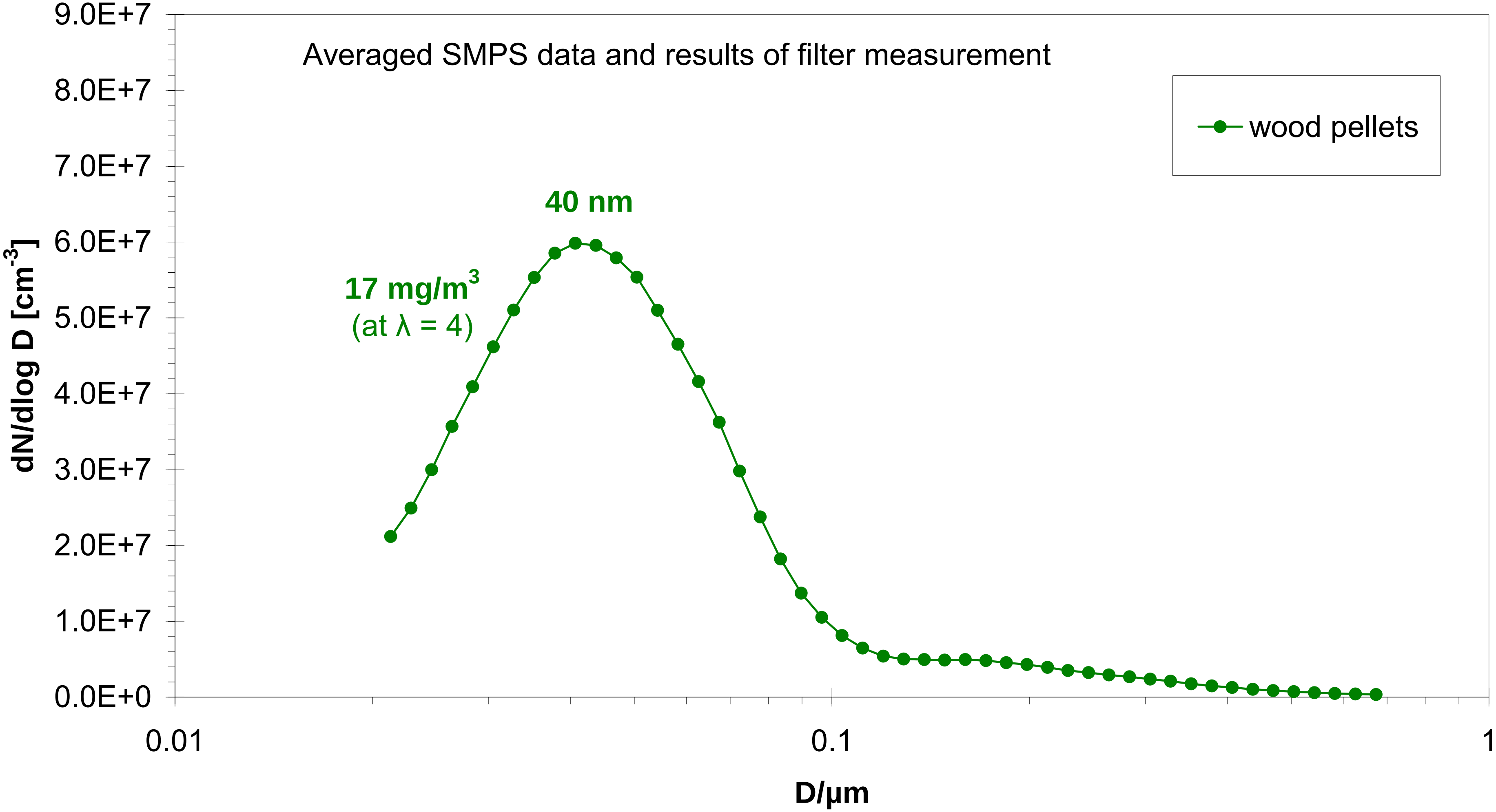


Incomplete Combustion

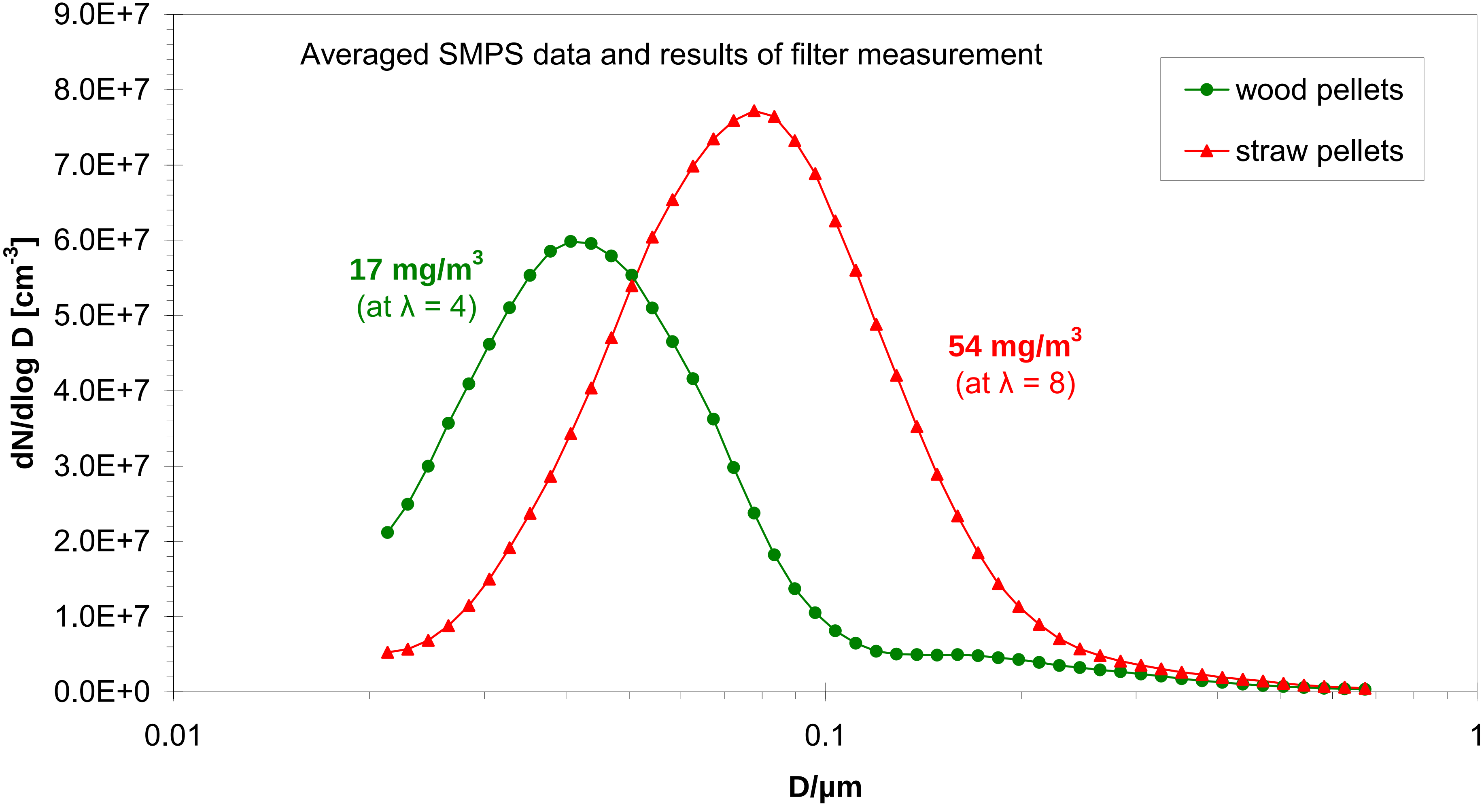
Stove on test bench, high emissions

Real life, February 2006

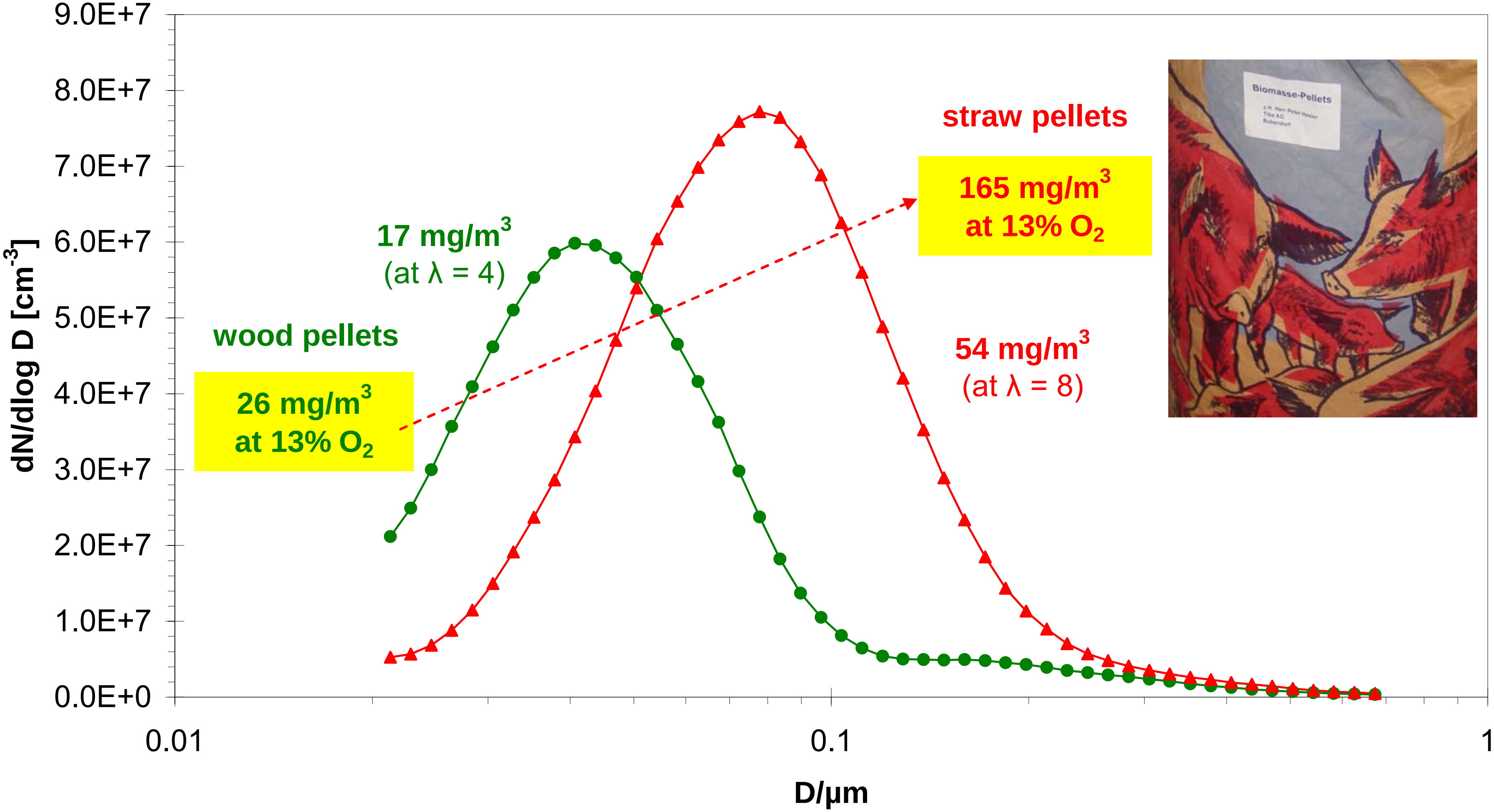
Pellet stove



Pellet stove



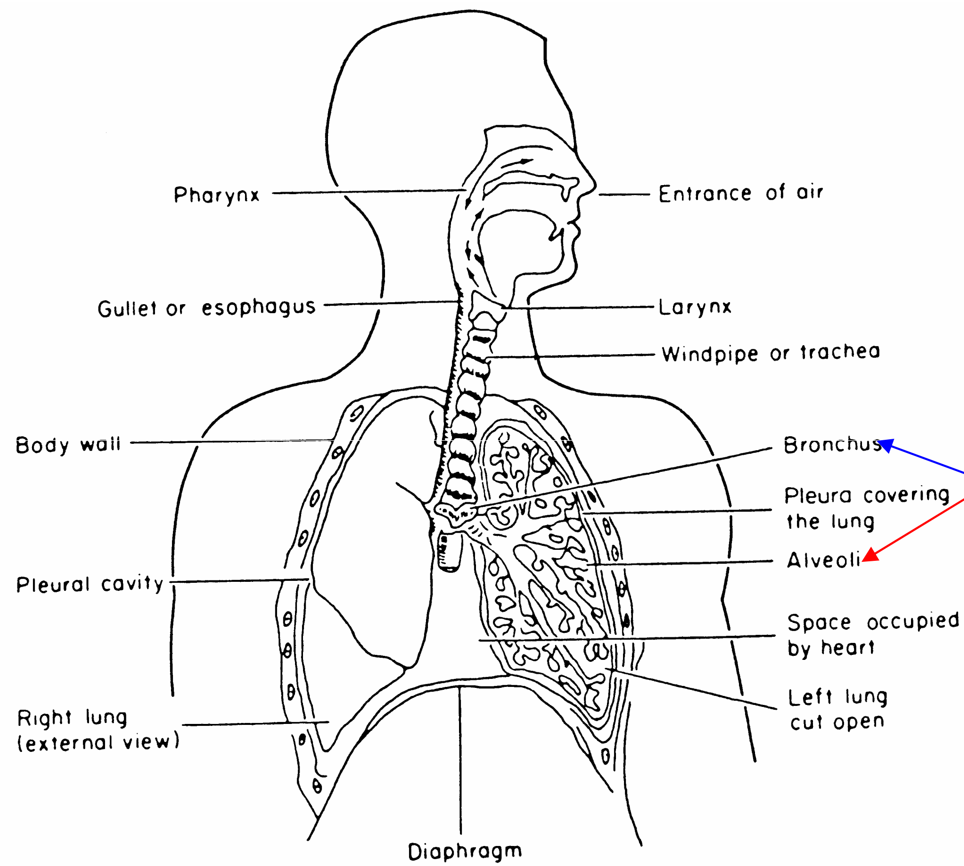
Pellet stove

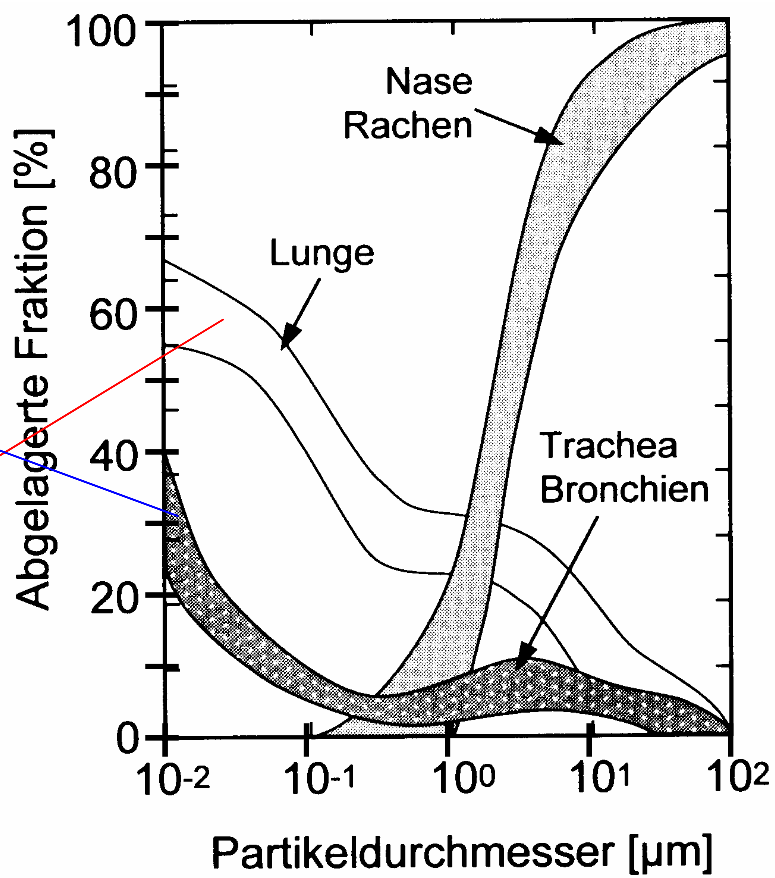


Particle Emissions from wood stoves

- Huge differences in emissions:
  - ≤ 30 mg/m^3 achieved in two-stage wood log stove and pellet stove
  - 50 mg/m^3 possible in conventional stove but only under optimal operation conditions
  - up to **5000 mg/m^3** possible in small metal stove under very bad operation conditions
- Particle size distribution shifted to larger particles under bad conditions, however:
- Emissions are dominated by particles below 2µm even at 5000 mg/m^3

Particle deposition in respitatory tract





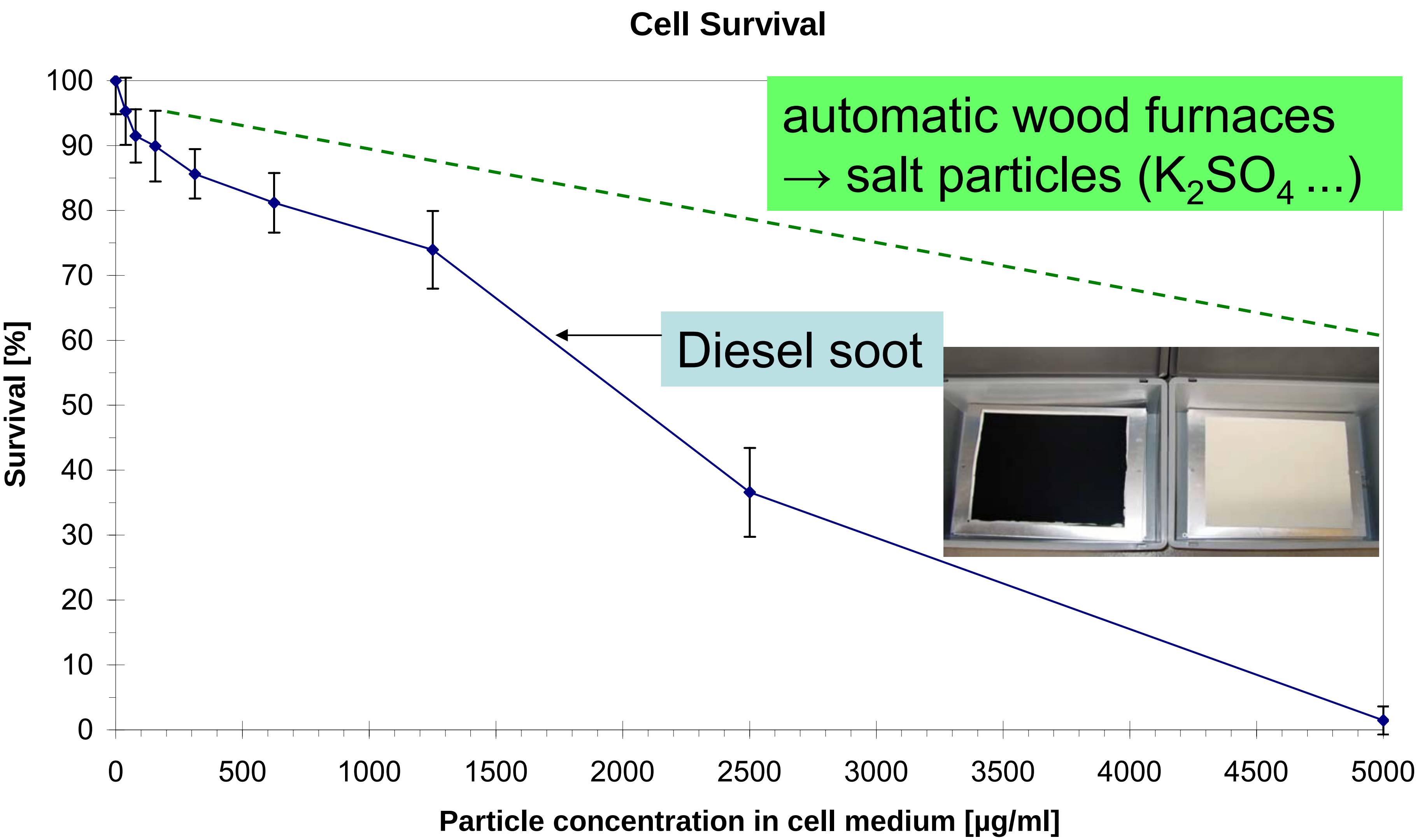
 [Boubel et al., 1994]

[Health Phys. 12, 173]

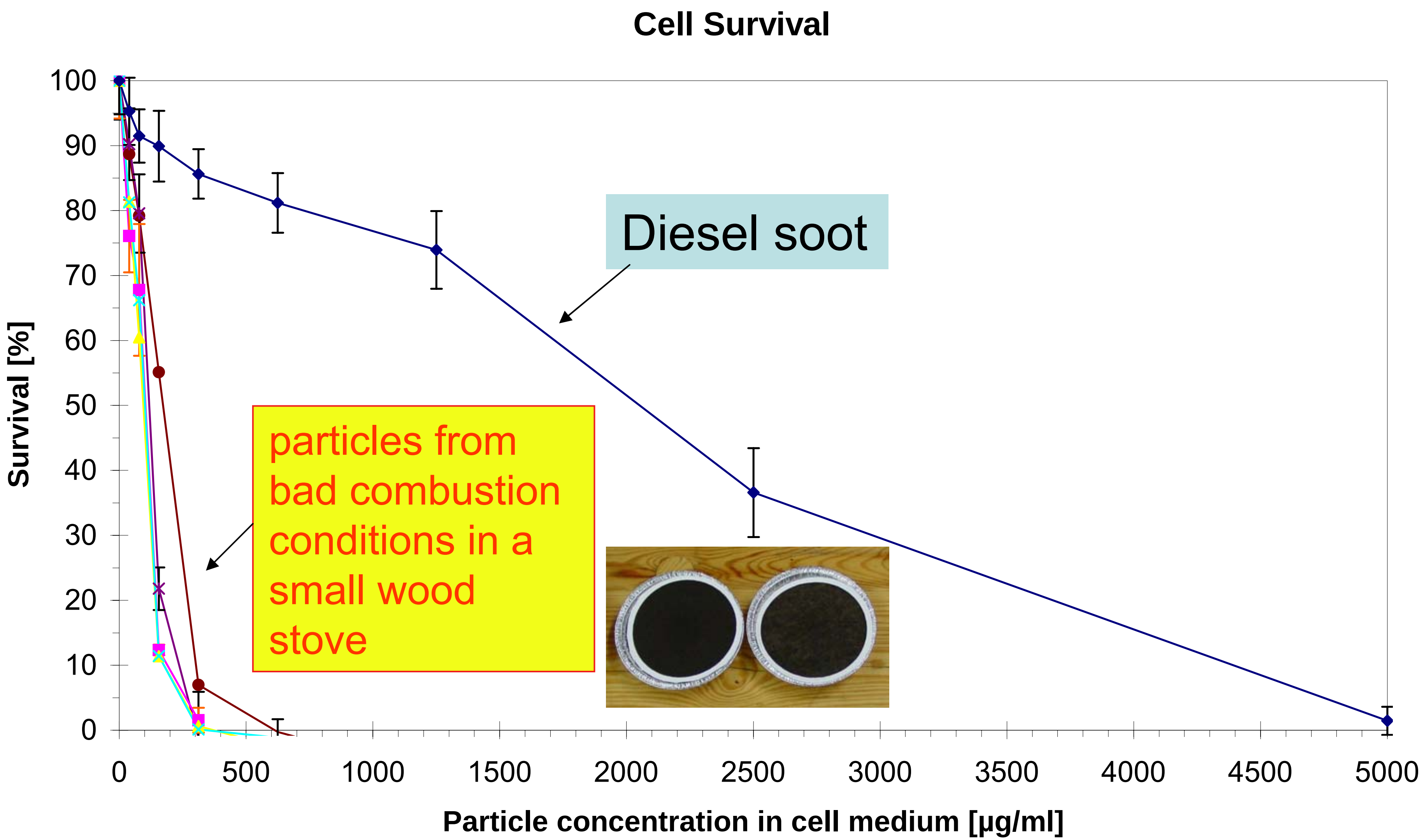
Health impacts of high emissions from small wood log stoves

- Predominant fraction of emitted particles inhalable (PM2.5 or PM1)
- Chemical analysis for bad combustion:
  - Particles consist mainly of soot (carbon and hydrocarbons), low amount of inorganic salts
  - Polycyclic aromatic hydrocarbons (PAH) fraction attached to particles is much higher than for Diesel soot
- Biological tests performed for sampled particles with V79 fibroblast cells of Chinese hamster

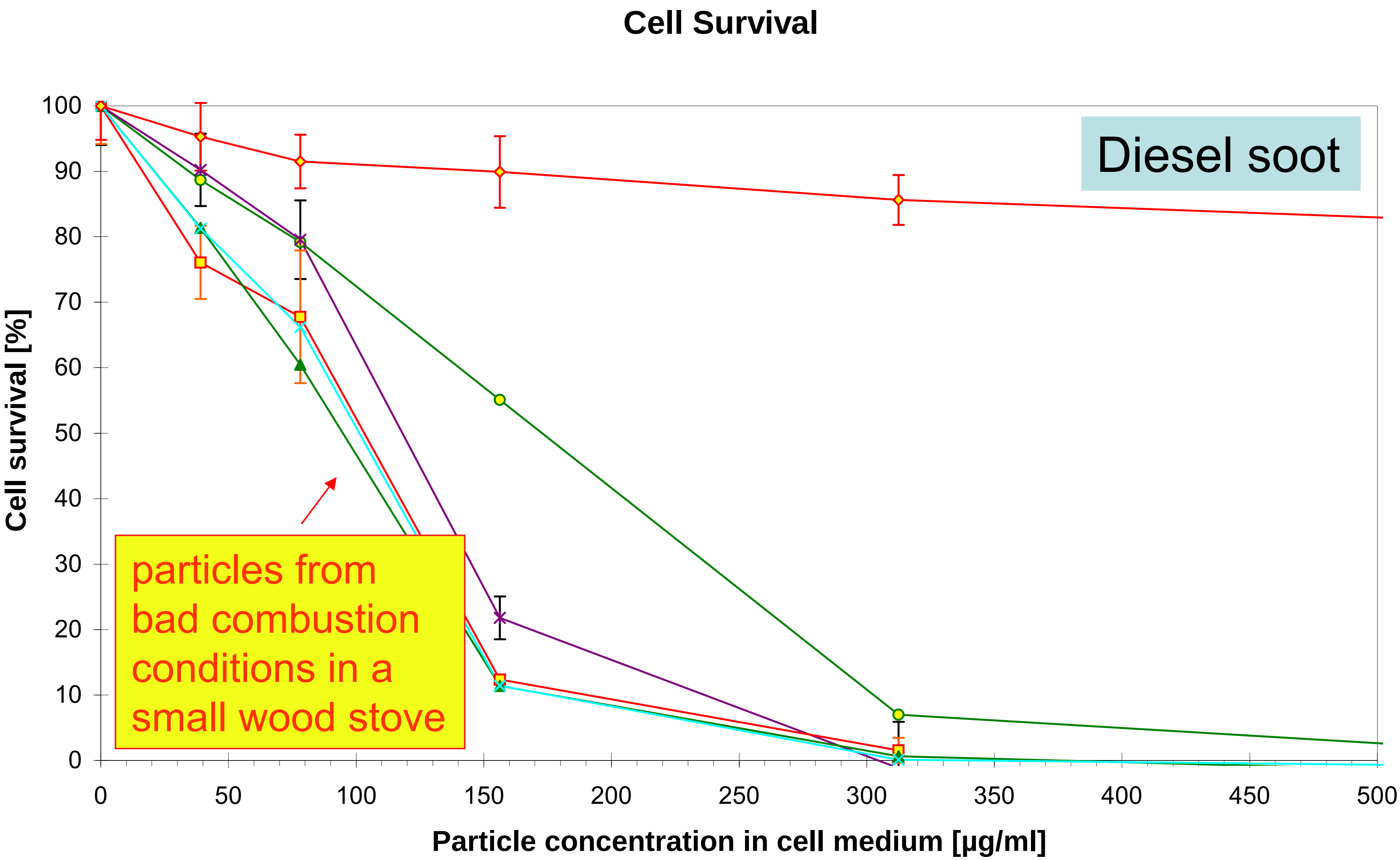
Results of Cytotoxicity Tests



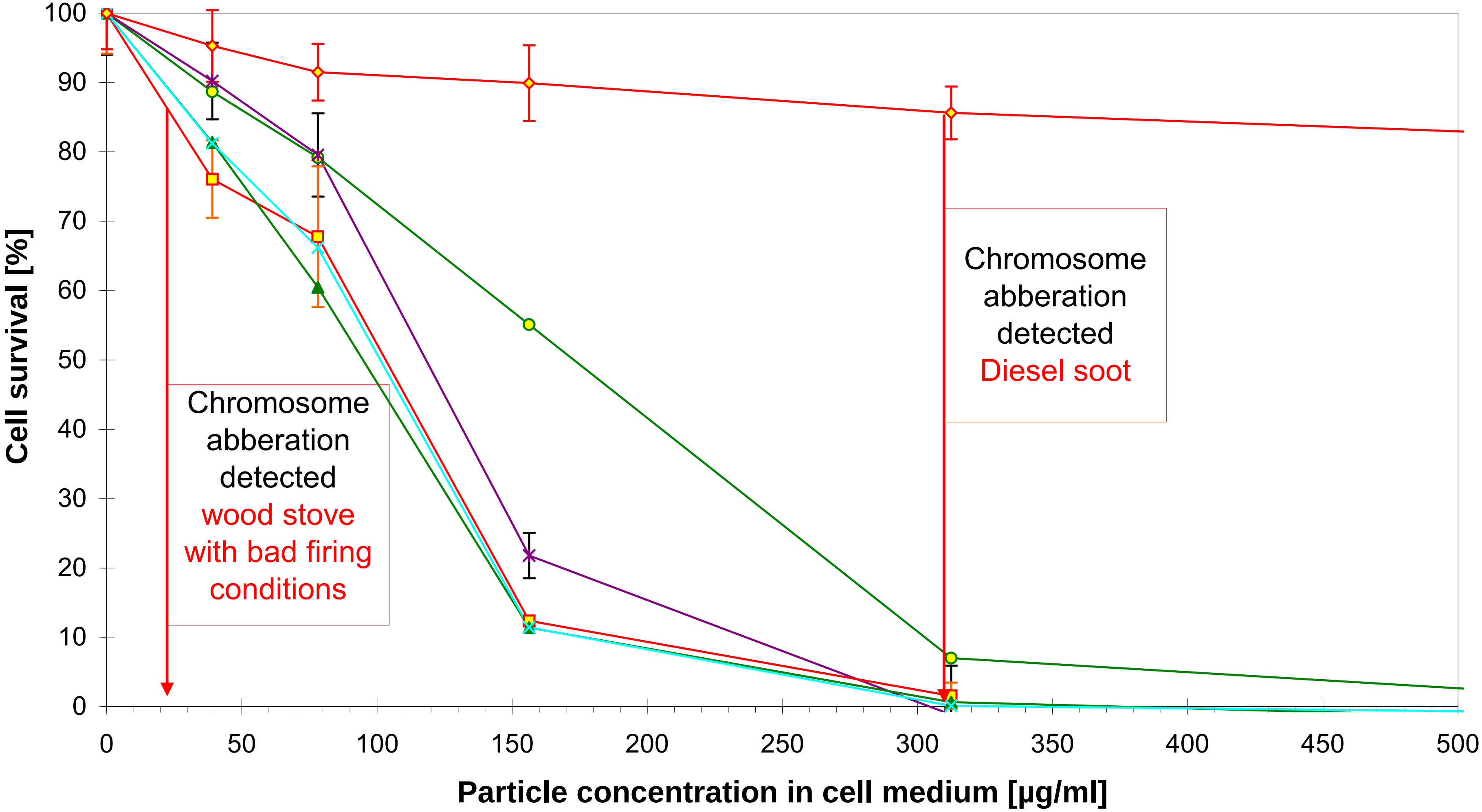
Results of Cytotoxicity Tests



Results of Cytotoxicity Tests



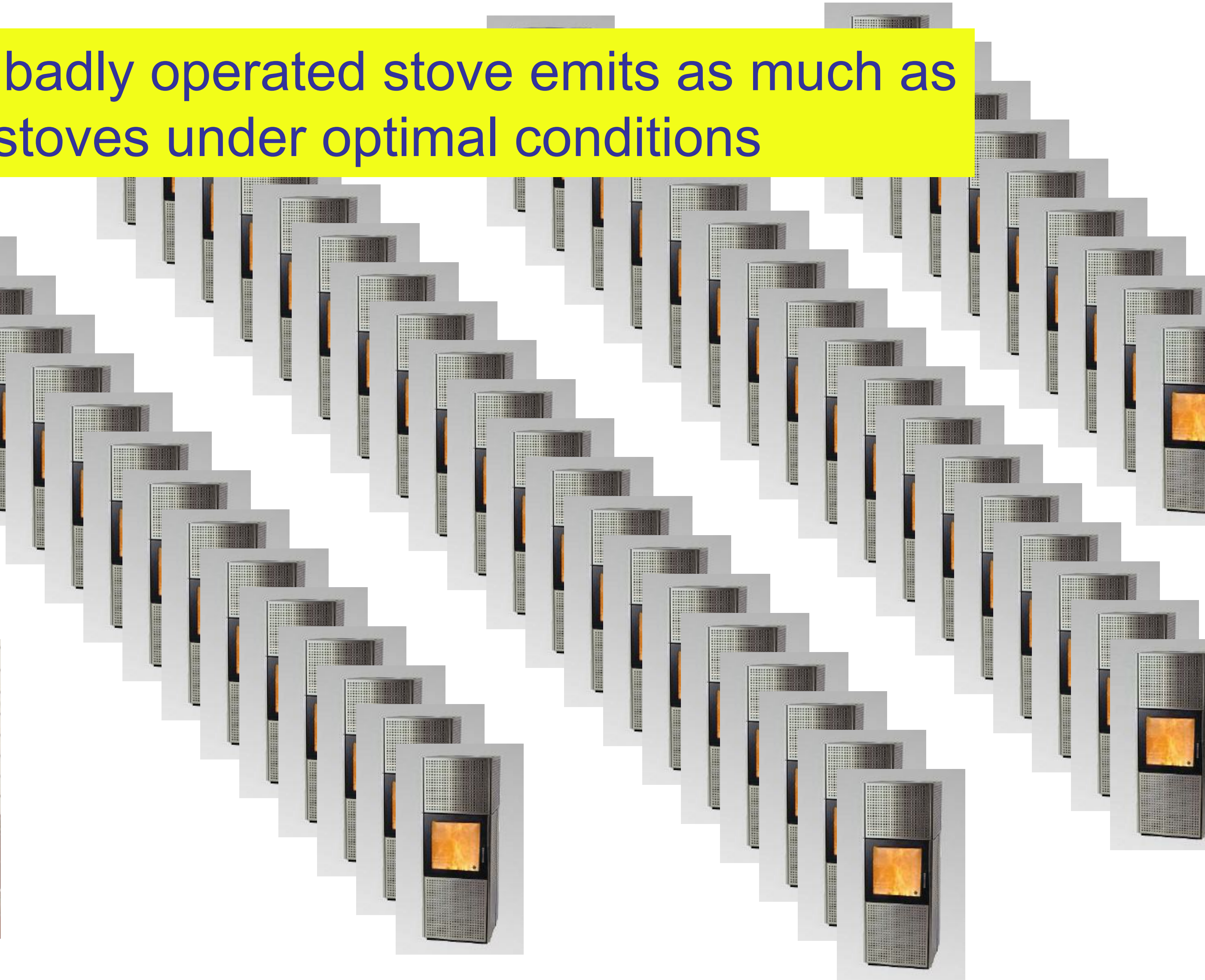
Carcinogenic potential estimated by observation of chromosome defects



Summary and Conclusions

- Huge variability in PM: < 20 mg/m^3 to > 5000 mg/m^3
- Conventional stoves
  - achieve low PM emissions at ideal conditions
  - exhibit strong influence of operating conditions
  - hence emission factors from wood may be under estimated
- Two-stage wood stove and pellet stove achieve < 50mg/m^3 safely with low influence of user
- Advantage not rewarded in present legislation
  → two-stage stove planned to be taken from market (!)
- Modified type approval is highly recommended
- Biological toxicity compared to Diesel soot particles:
  - higher for bad wood log combustion (soot)
  - lower for automatic furnaces (inorganic salts)

Comparison of emission factors...



One badly operated stove emits as much as 100 stoves under optimal conditions

...and real life

Acknowledgements

- Swiss Federal Office of Energy (SFOE), Berne
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- Tiba AG, Bubendorf, Switzerland
- RCC Cytotest Cell Research, Darmstadt, Germany
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Back-up Slides

Incomplete combustion in a small metal stove

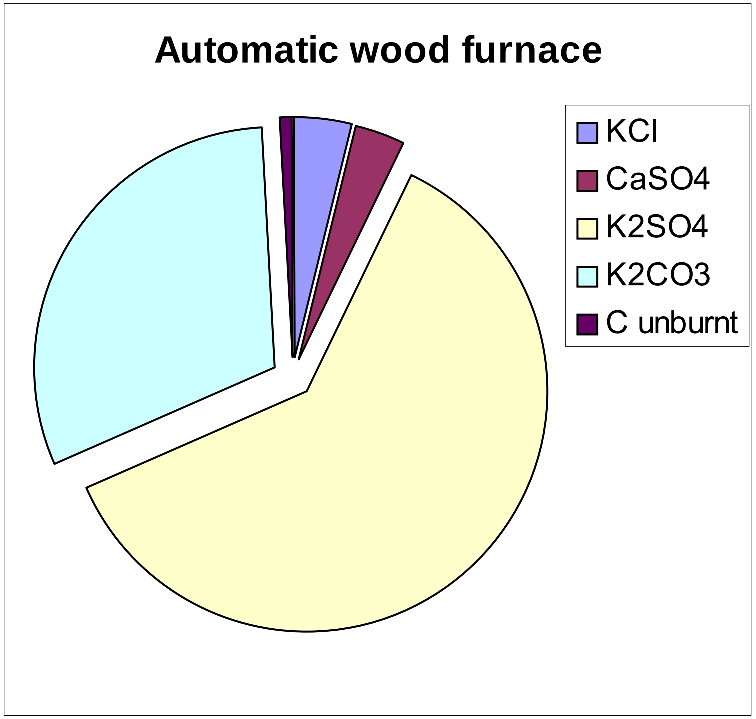
EPA sampling train after heated filter
- very bad conditions with filter break-through

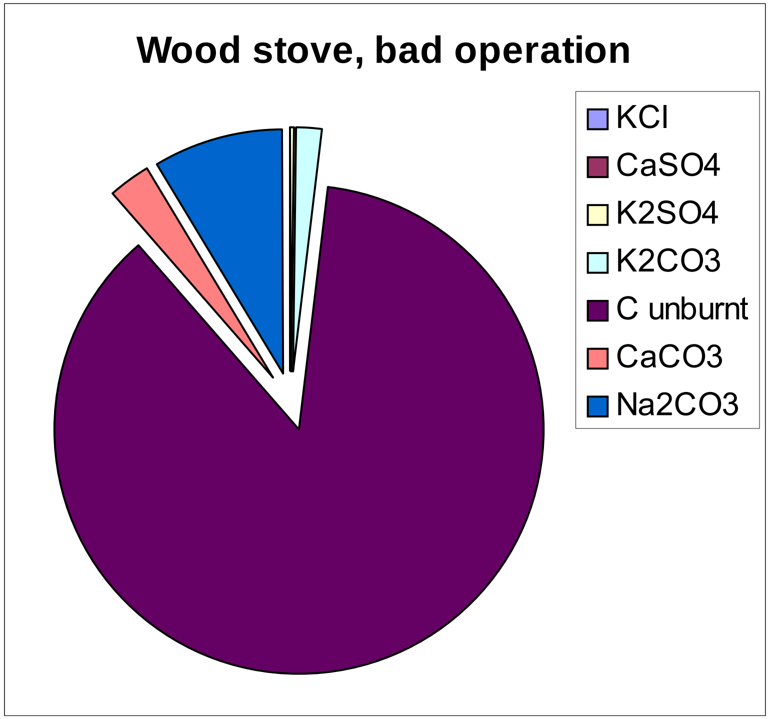
Samples from bad combustion conditions in a small metal stove

Particle emissions > 1 g/m^3

CO emissions ≈ 1 %

Chemical Composition of Particles
for different types of wood combustion

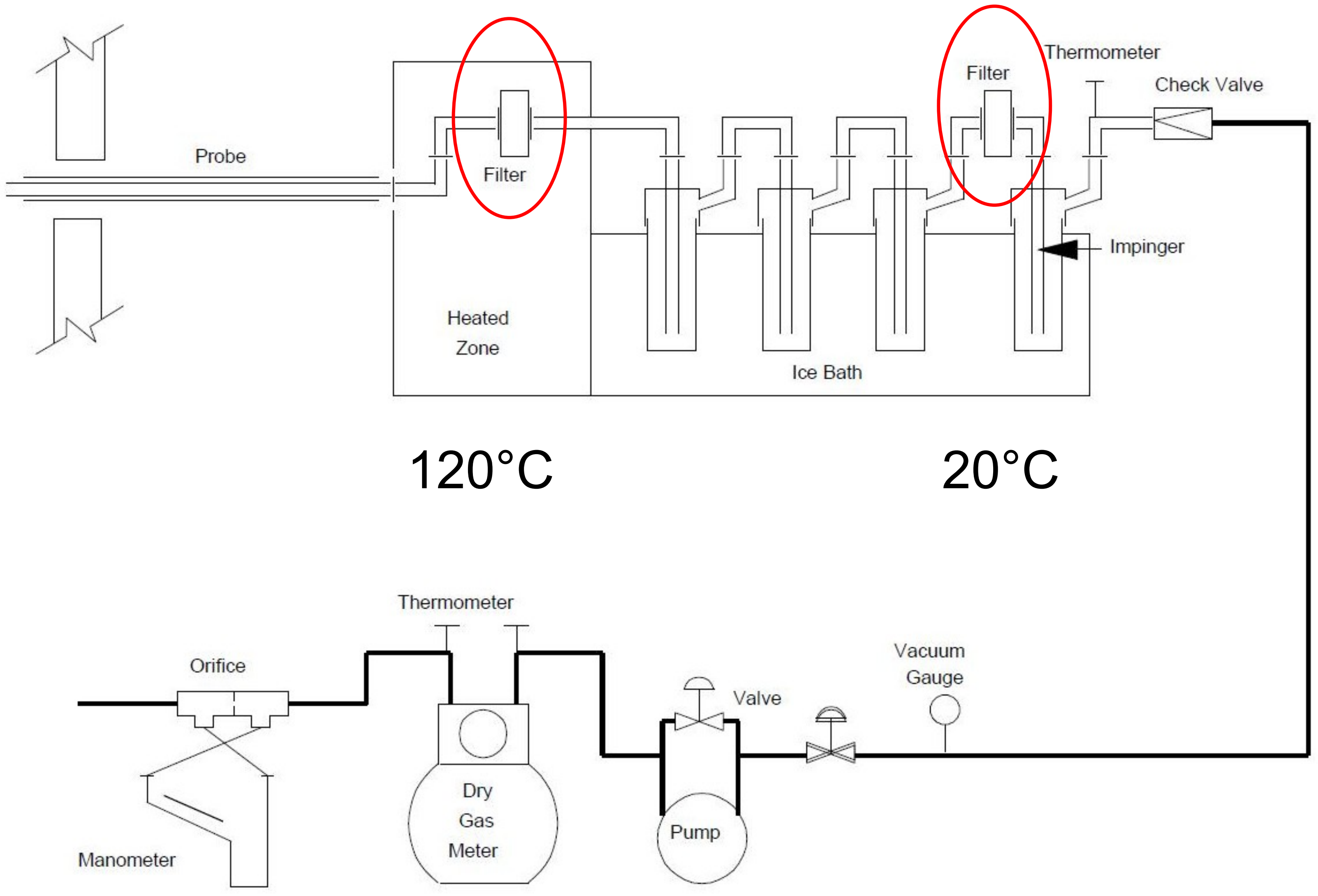




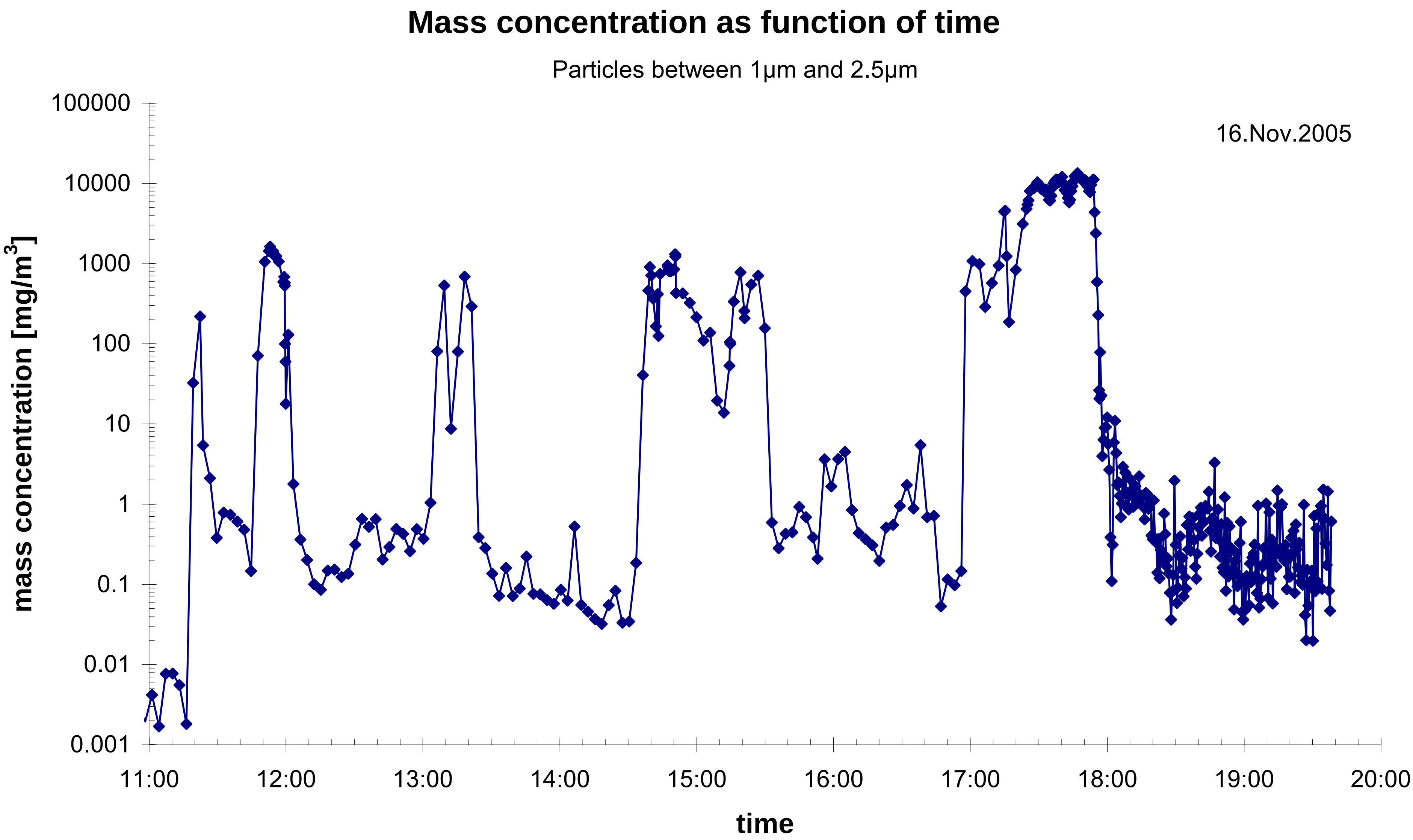
Dominated by inorganic salts, < 2.5% carbon

Dominated by unburnt carbon (soot)

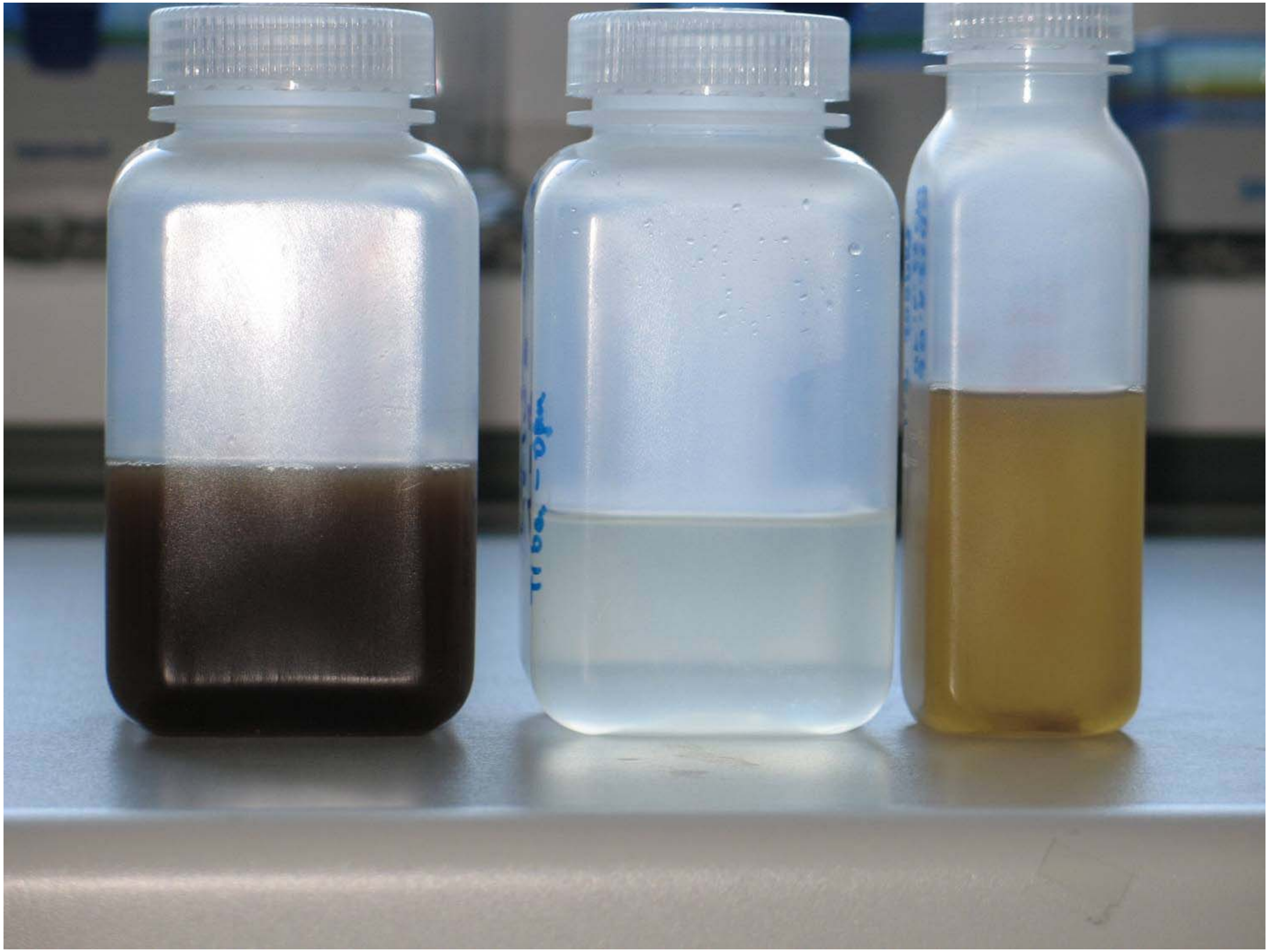
Sampling according to EPA method 5H



Incomplete combustion in a small metal stove

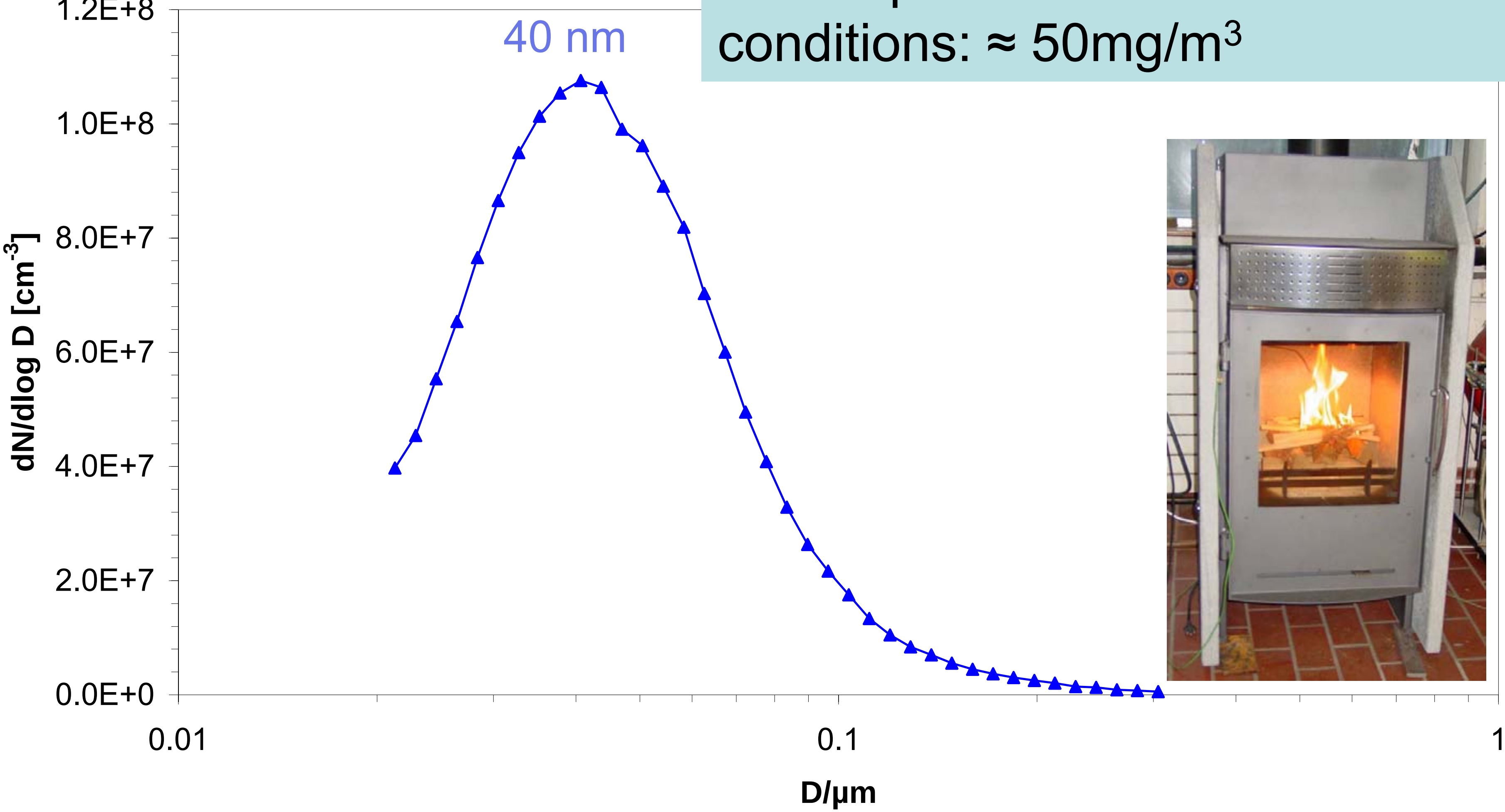


Contents of impingers for different operation

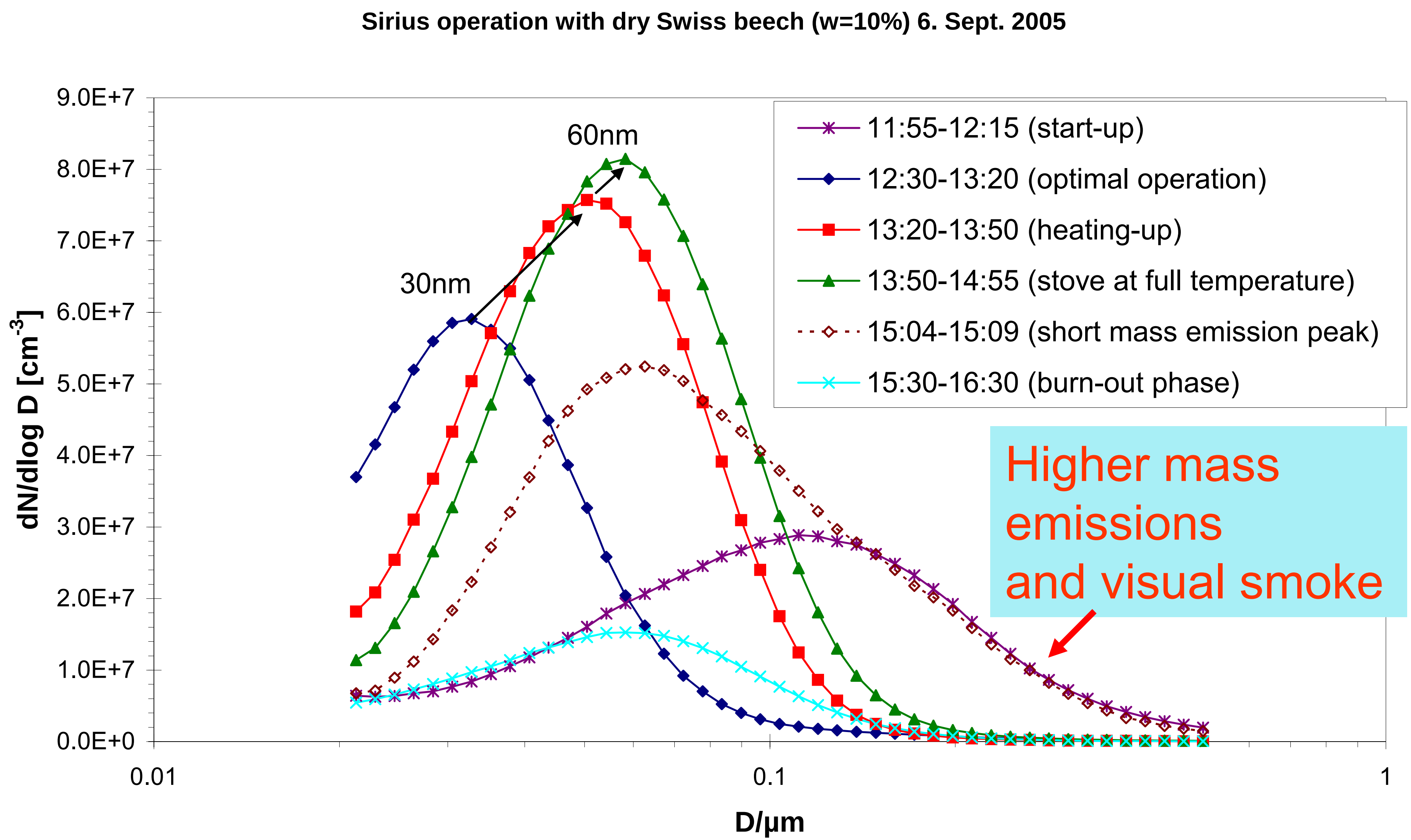


Conventional stove

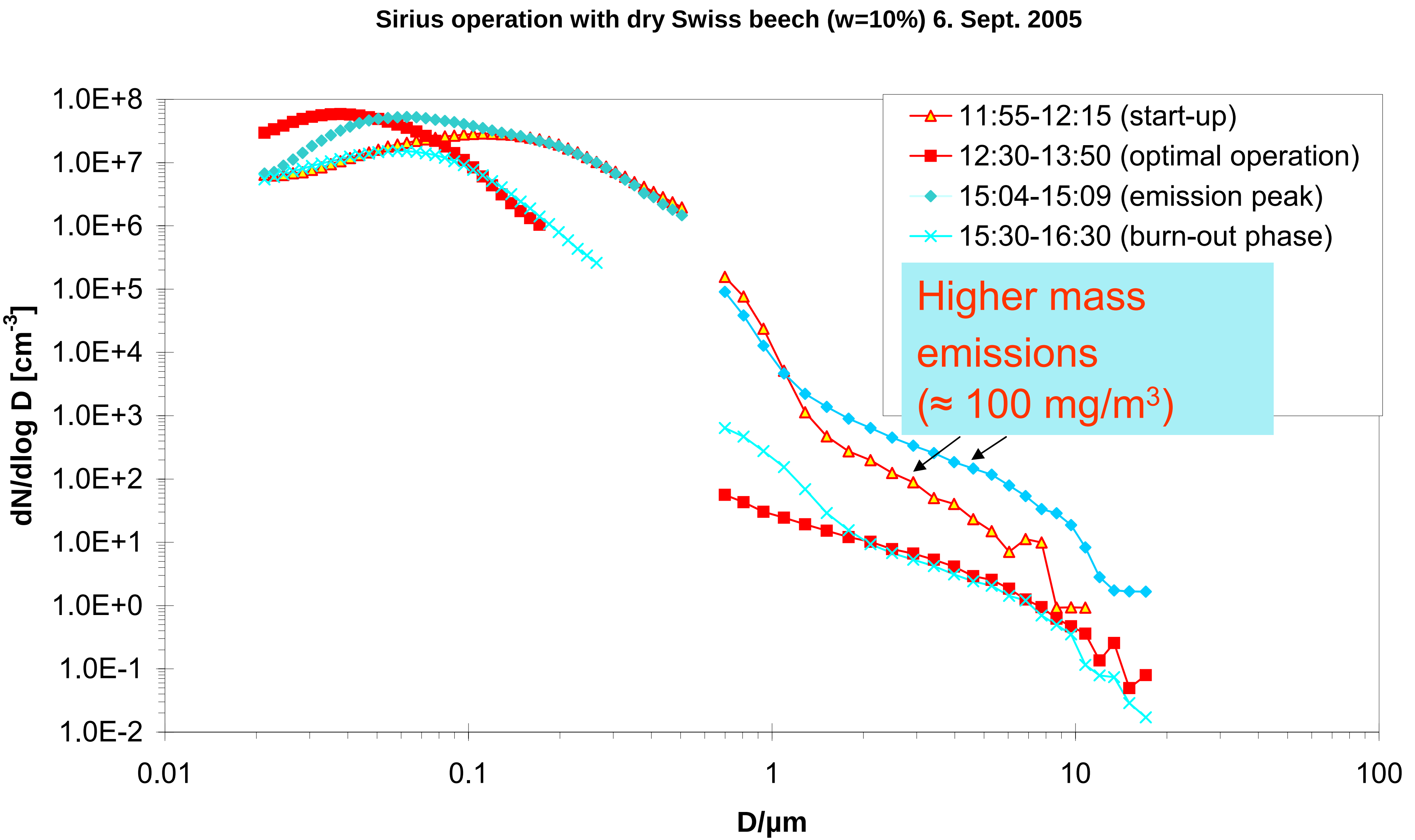
stove operated under ideal conditions: ≈ $50 mg/m^3$



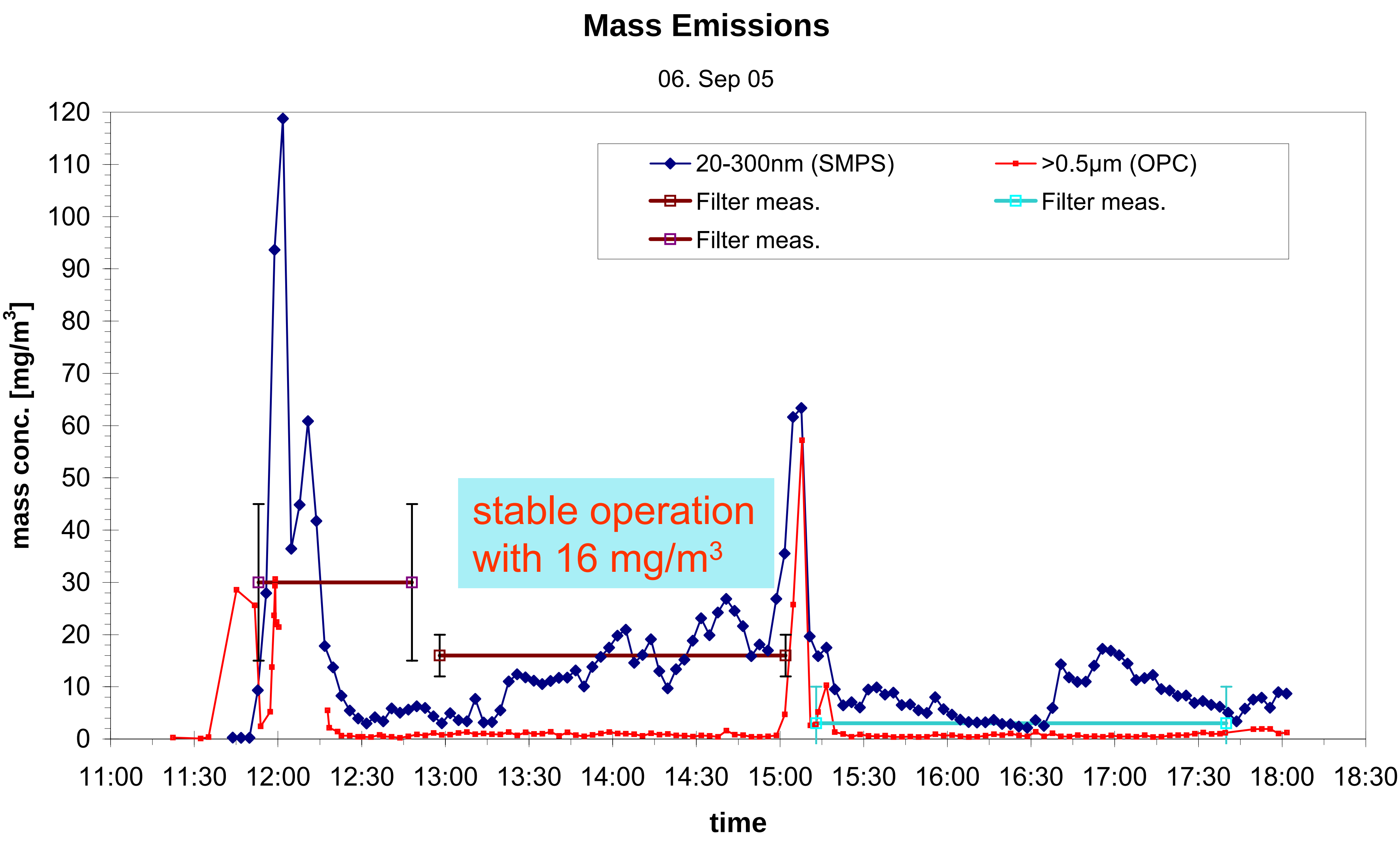
Two-stage combustion: start-up



Two-stage combustion: start-up



Two-stage combustion



Previous results from an automatic wood furnace with low particle emissions

0.5 g particle mass

2 g particle mass

Particles from automatic wood furnace compared to Diesel soot