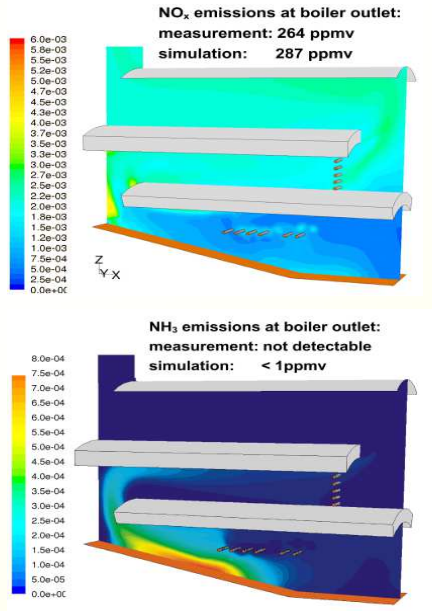
# $NO_x$ emissions from biomass combustion plants

**DI Dr. Ingwald Obernberger**

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# Content

- N content of different biomass fuels
- Mechanisms of $NO_x$ formation
- $NO_x$ emission reduction potential of different technologies
- $NO_x$ emissions and N conversion related to the N content of the fuel
- Investigation of release profiles based on lab-scale reactor tests
- CFD simulations of $NO_x$ emissions
- $NO_x$ reduction by primary measures
- $NO_x$ reduction by secondary measures
- Summary and conclusions

N content of different biomass fuels

Mechanisms of $NO_x$ formation

$NO_x$ emission reduction potential of different technologies

$NO_x$ emissions and N conversion related to the N content of the fuel

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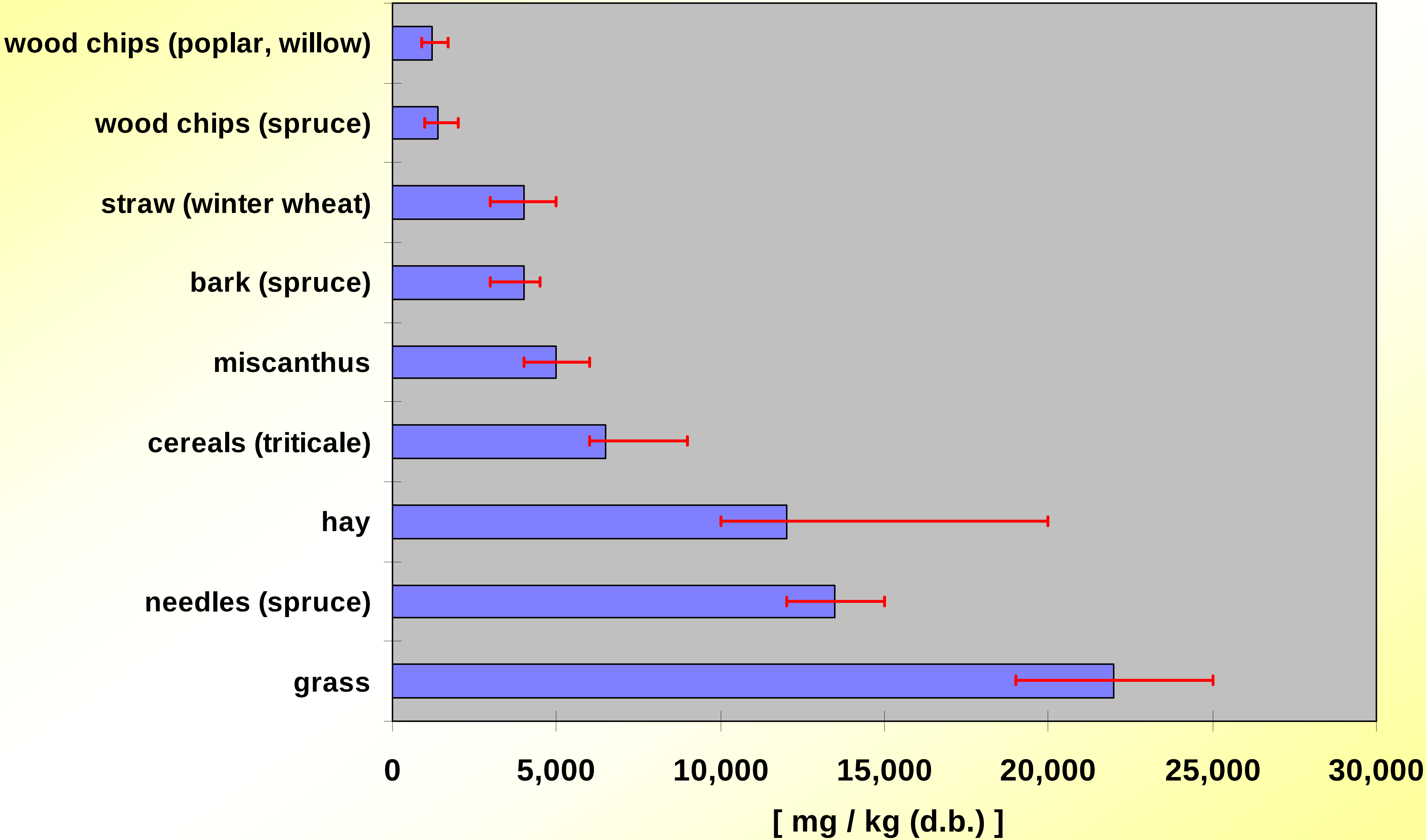
# $NO_x$- emissions - N-content of different biomass fuels

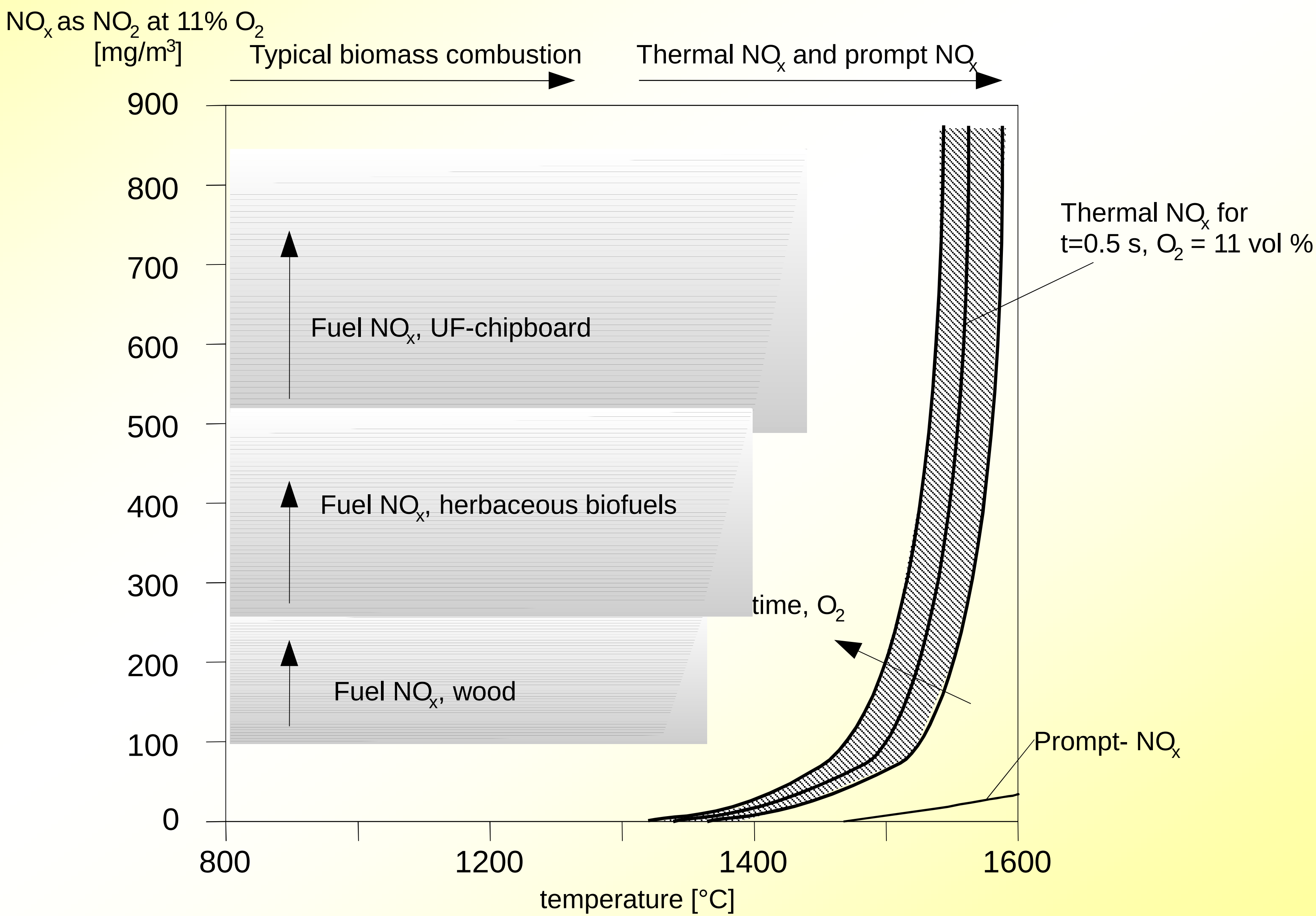


# Mechanisms of $NO_x$ formation:

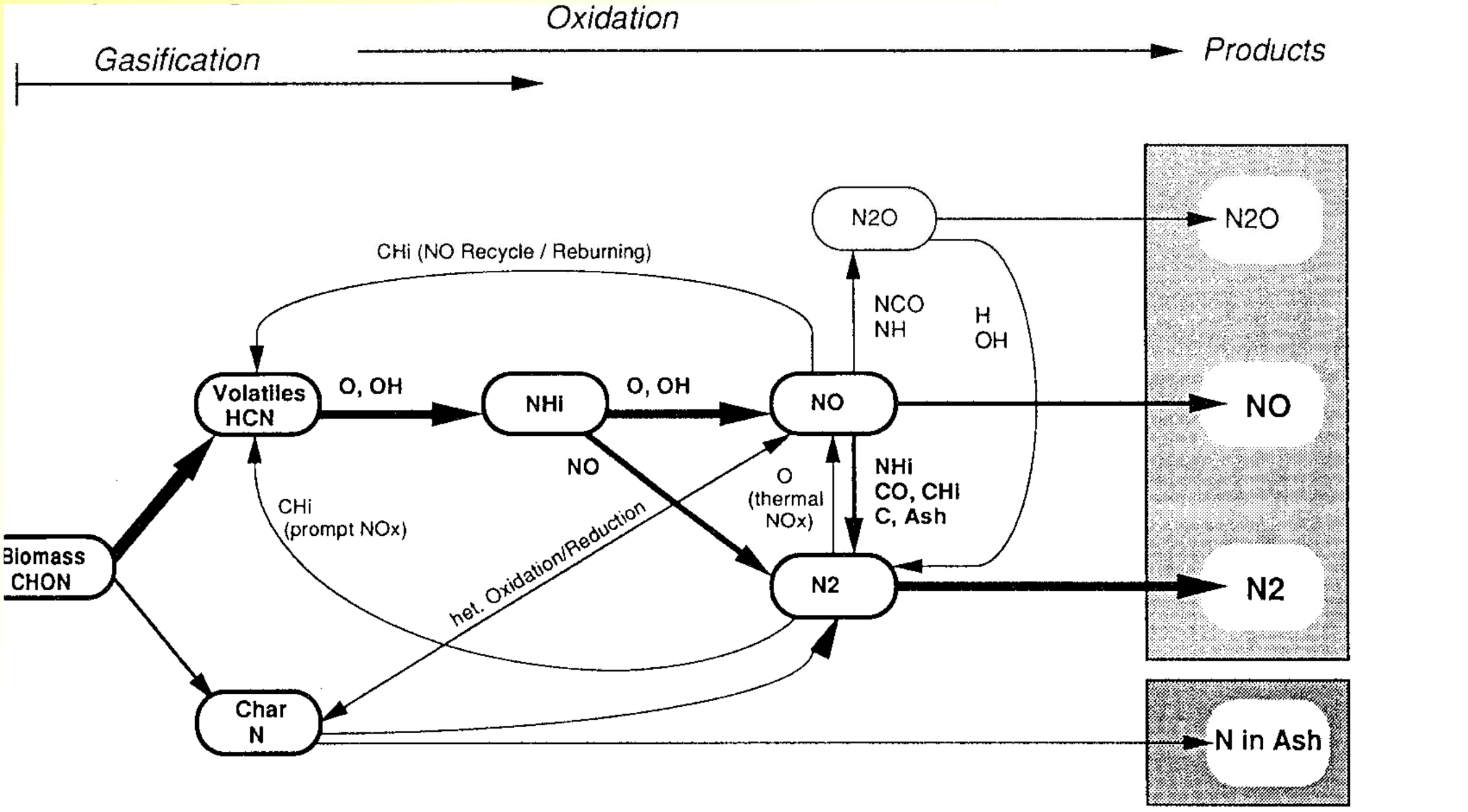
- thermal $NO_x$
- prompt $NO_x$
- fuel $NO_x$

($NO_x$ is the sum of the nitric oxides NO and $NO_2$)

# $NO_x$-emissions - dependence on the fuel and the furnace temperature



# $NO_x$-emissions - reaction paths of fuel-N



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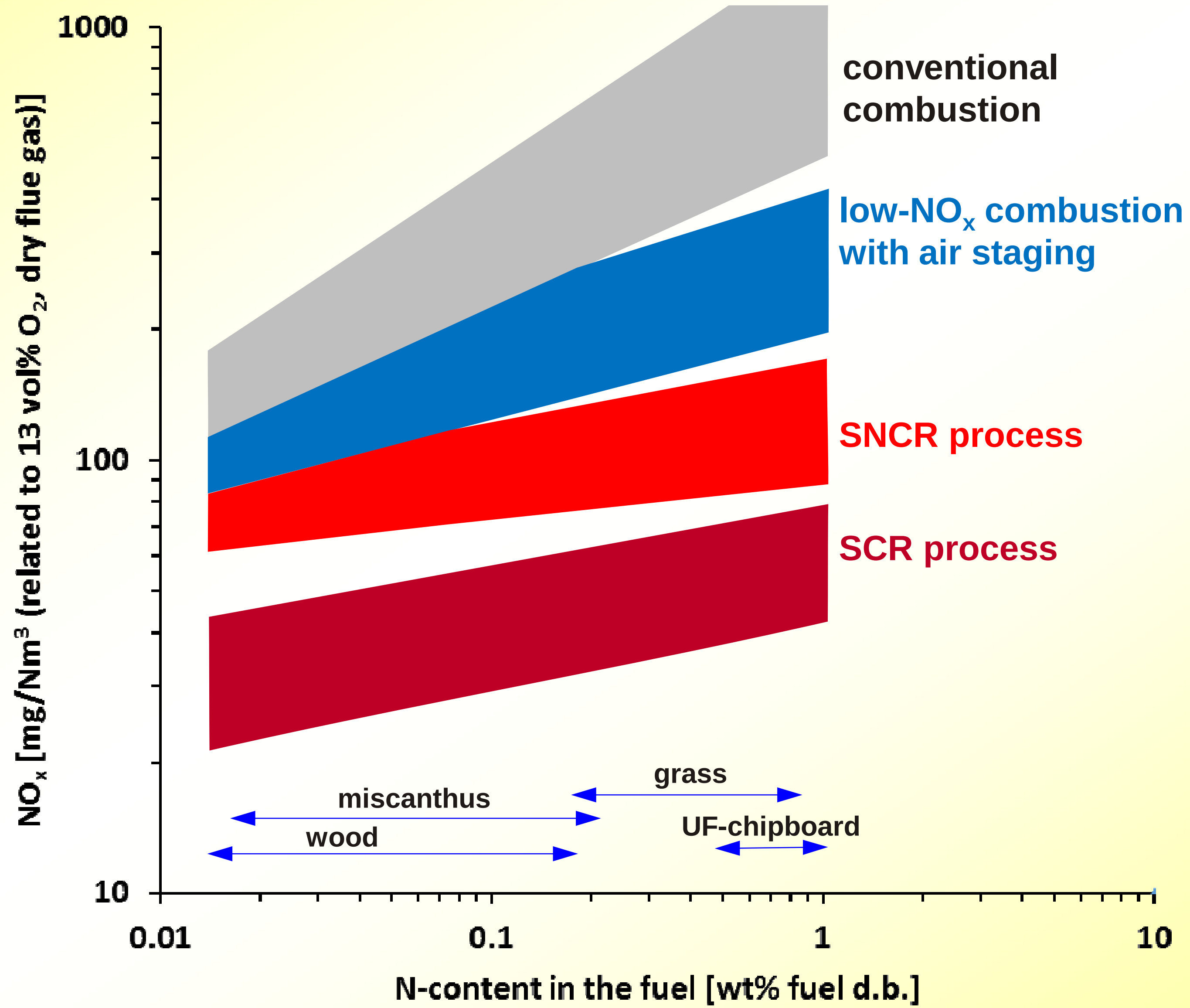
# $NO_x$ emission reduction potential of different technologies



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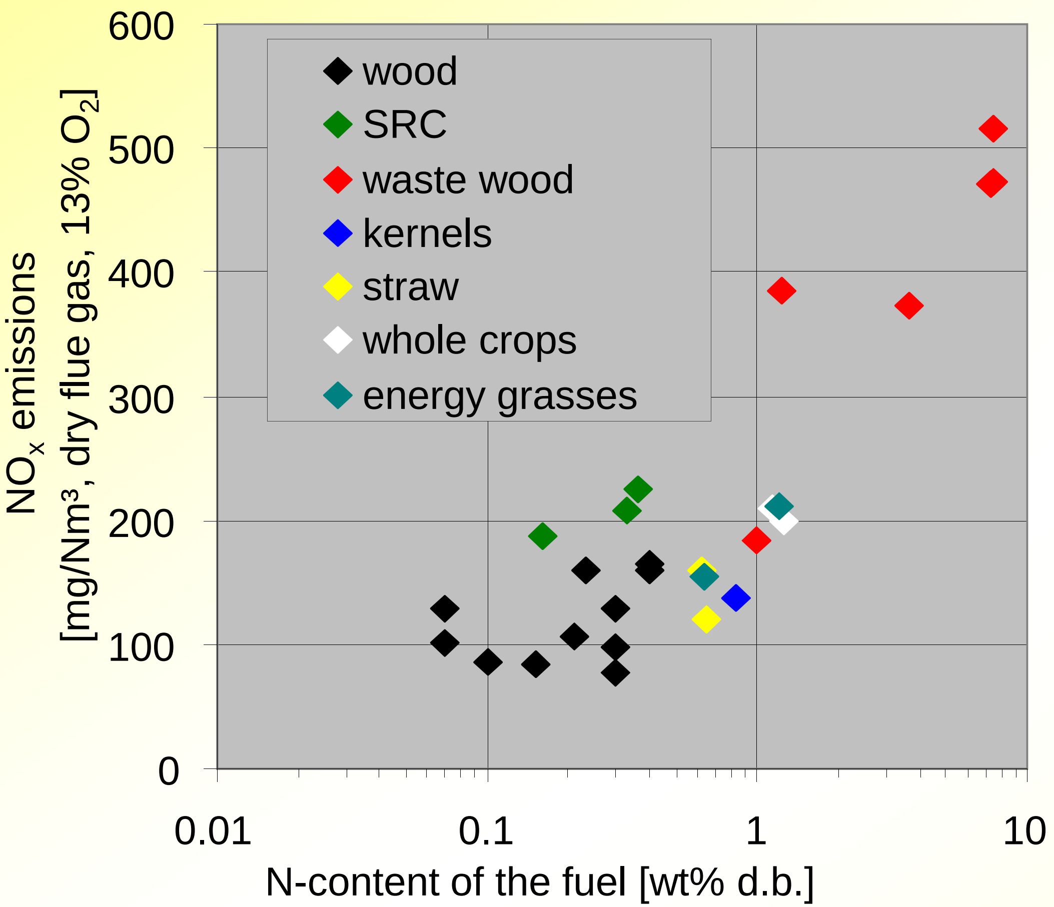
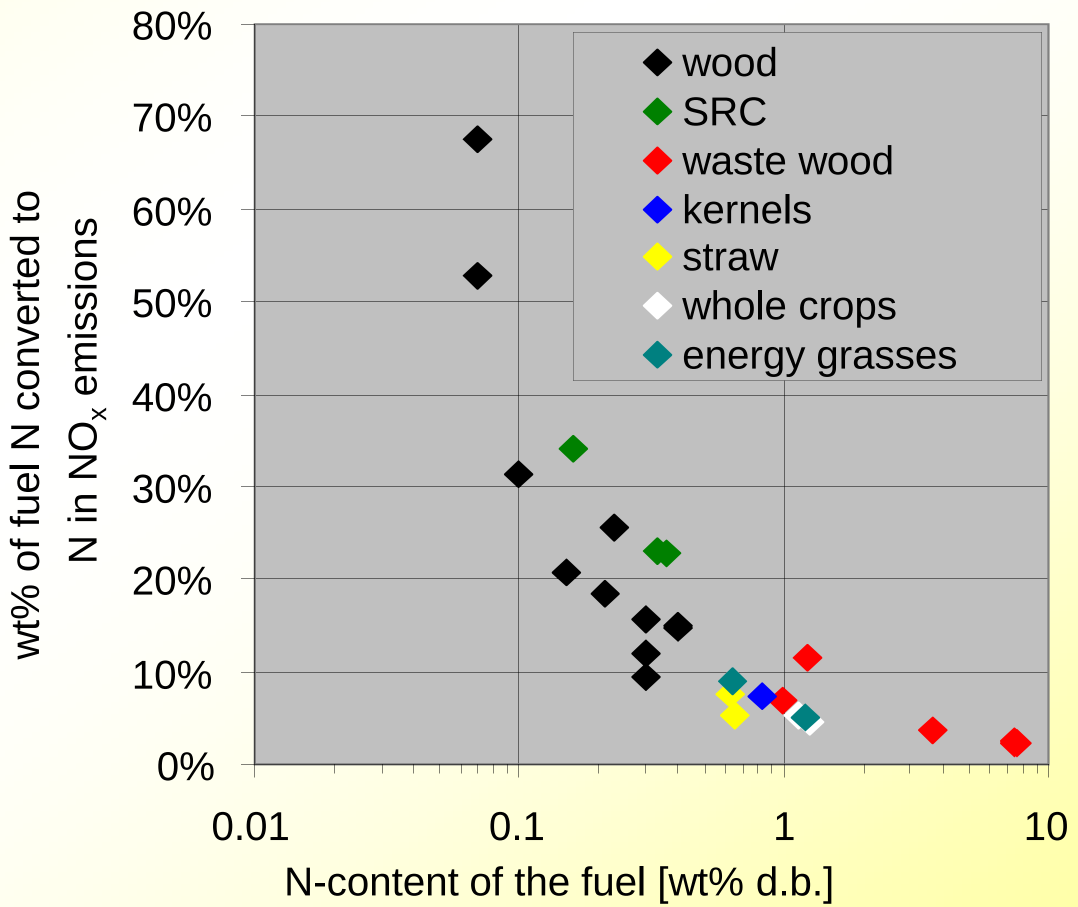
# $NO_x$ emissions and N-conversion related to the N content of the fuel




$NO_x$ calculated as $NO_2$

Results of test runs at real-scale plants equipped with air staging technology

# Investigation of release profiles based on lab-scale reactor tests

# Lab-scale reactor tests – Introduction and objectives

Due to wide variations in fuel composition, the combustion behaviour of different biomass fuels cannot be predicted only on a theoretical basis.

In order to examine relevant combustion characteristics of biomass fuels in grate combustion systems a specially designed lab-scale reactor was developed.

The purpose of this reactor is to gain information regarding

- fuel decomposition behaviour
- release behaviour of $NO_x$ precursors
- release behaviour of aerosol forming elements (K, Na, Zn, S and Cl)
- slagging behaviour (first indications)

# Description of the lab-scale reactor – general aspects

## Constraints for the reactor design

- Simulation of the fuel behaviour in grate combustion systems (packed bed)
- Reasonable sample intake in order to simulate secondary reactions in the fuel bed appropriately
- High heating rates of the fuel comparable with real-scale grate furnaces
- Inert reactor material in order to avoid reactions of the gases with the reactor
- High flexibility regarding analytical equipment connected with the reactor
- Online recording of relevant operation data and emissions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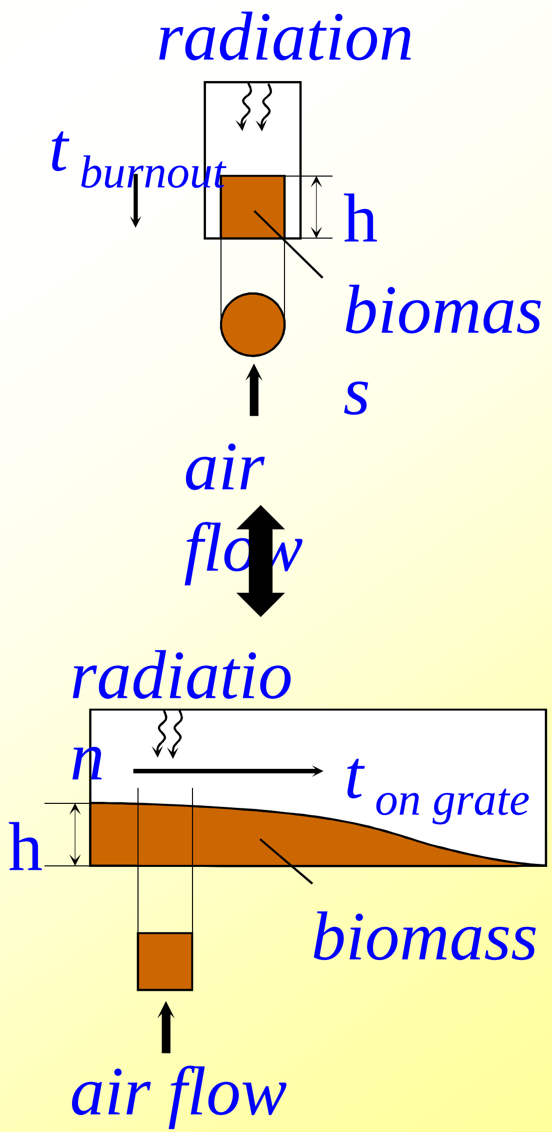
# Description of the lab-scale reactor

- **Batch type reactor**
- **Electrically heated retort made of fibre reinforced silica carbide (SiC)**
- **Two independently controllable heating zones (the fuel layer is heated by radiation from above and beside the fuel bed)**
- **Sample holder (also made of SiC) is placed on a balance for on-line mass loss detection**
- **The reaction medium (e.g. air, $N_2$ or mixtures of $N_2$ and $O_2$) flows through a perforated bottom plate**
- **Sample holder sealing is realised with thermal oil**

# Experimental approach

- **Energy input via radiation from the upper heating element (radiation section)**
- **Energy input into the bed zone via the lower heating element (bed section)**
- **Primary combustion air is supplied from below the grate**
- **Under consideration that the fuel transport along the grate can be compared with a plug flow, the time dependent results of the lab-scale reactor can be correlated to the local burning conditions on a grate**
  - **drying phase**
  - **pyrolysis/gasification**
  - **charcoal burnout**



# Measurements, sampling and analyses – on-line measurements

- Mass reduction of the sample (scale)
- Flue gas composition
  - FTIR (Ansyco DX-4000): $CO_2$, CO, $CH_4$, $H_2O$, NO, $NH_3$, HCN, $NO_2$, $N_2O$, basic hydrocarbons
  - Emerson NGA 2000: Paramagnetism: $O_2$; NDIR: $CO_2$, CO; heat conductivity: $H_2$
  - FID (Bernath Atomic 3005): OGC ($C_xH_y$)
  - CLD (ECO Physics CLD 700 EL ht): NO, $NO_x$
  - Lambda-sensor: $O_2$
- Temperature measurements
  - 5 thermocouples in the fuel bed (at three different vertical positions)
  - Thermocouples in the flue gas above the fuel bed
- Combustion air flow
- Pressure in the reactor

# Measurements, sampling and analyses – sampling and analyses

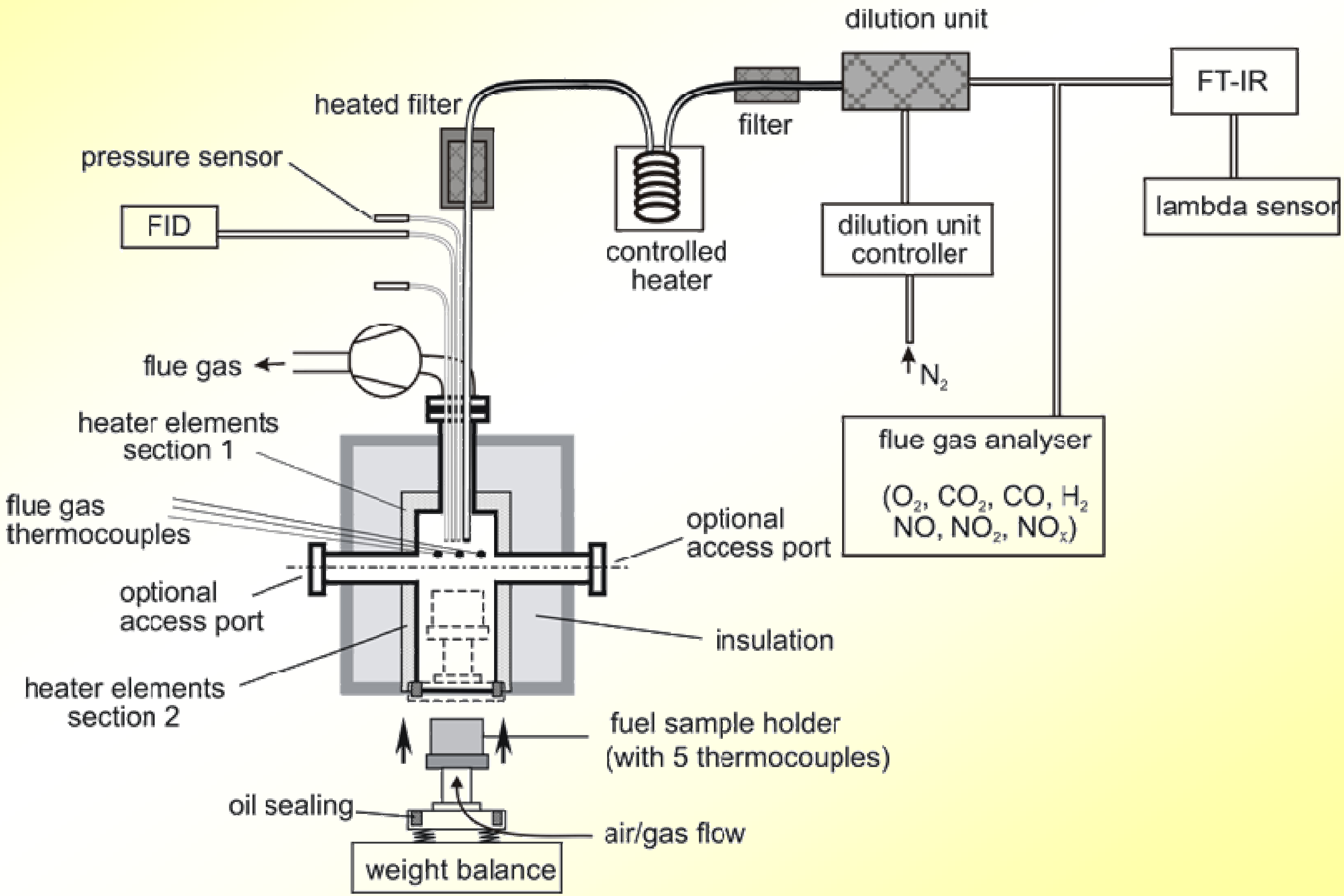
**Fuel sampling and analyses**

**(C, H, N, ash content, moisture content, S, Cl, major and minor ash forming elements)**

**Ash sampling and analyses**

- **optical evaluation**
- **chemical analyses (TOC, TIC, major and minor elements)**

# Measurements, sampling and analyses – reactor scheme



# Evaluation strategy and plausibility checks (II)

## Evaluations

- Evaluation of characteristic data describing the thermal fuel decomposition
  - start and duration of the volatilisation and charcoal gasification phase
  - start and duration of the main charcoal combustion phase
  - maximum fuel bed temperatures measured during these phases
  - decomposition rates determined during these phases
- Evaluation of the gas phase measurements
  - trend of the main flue gas species and $NO_x$ precursors
  - trend of the excess air ratio over the whole test run
- Evaluations based on the results from the fuel and ash analyses
  - release of ash forming elements

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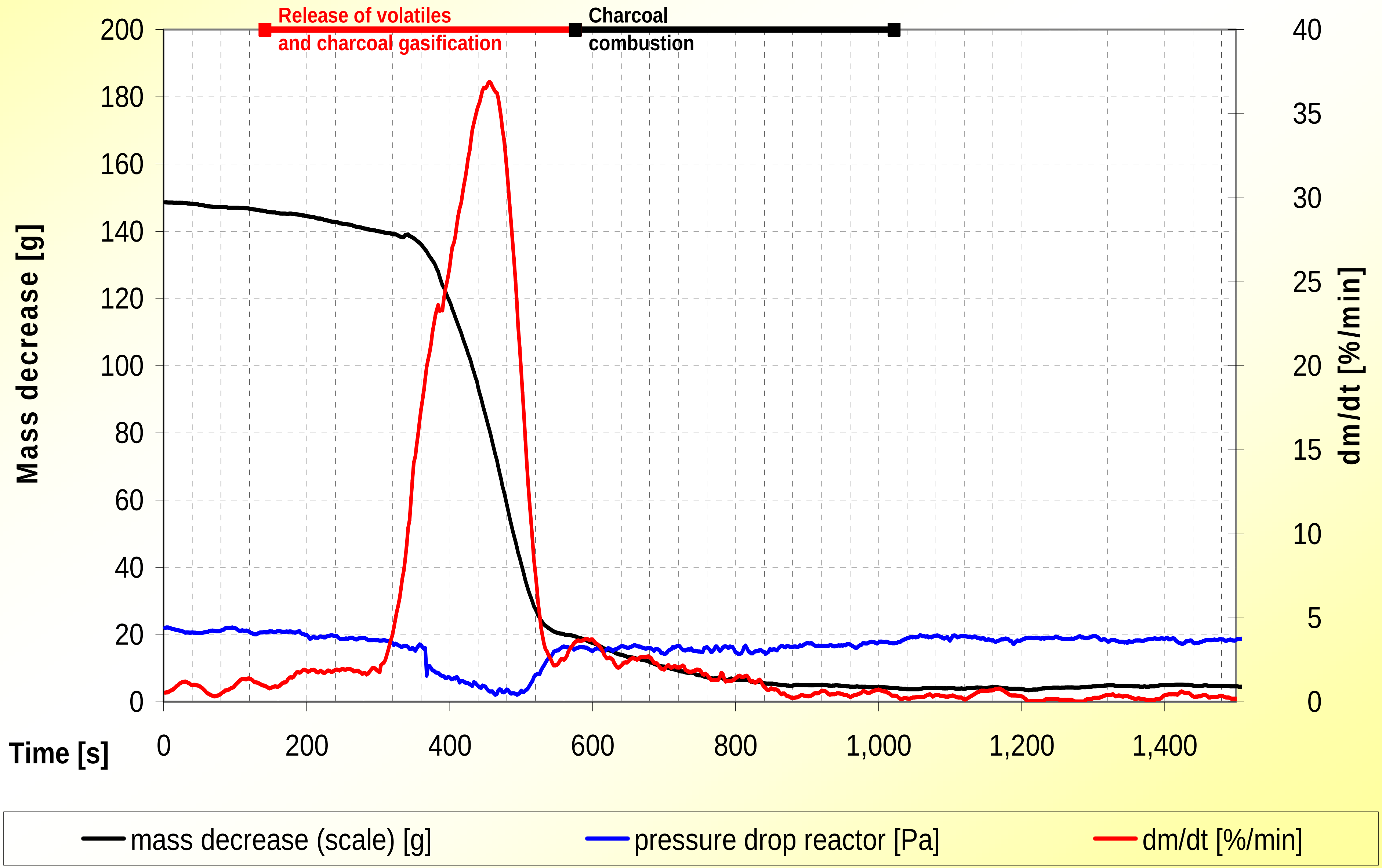
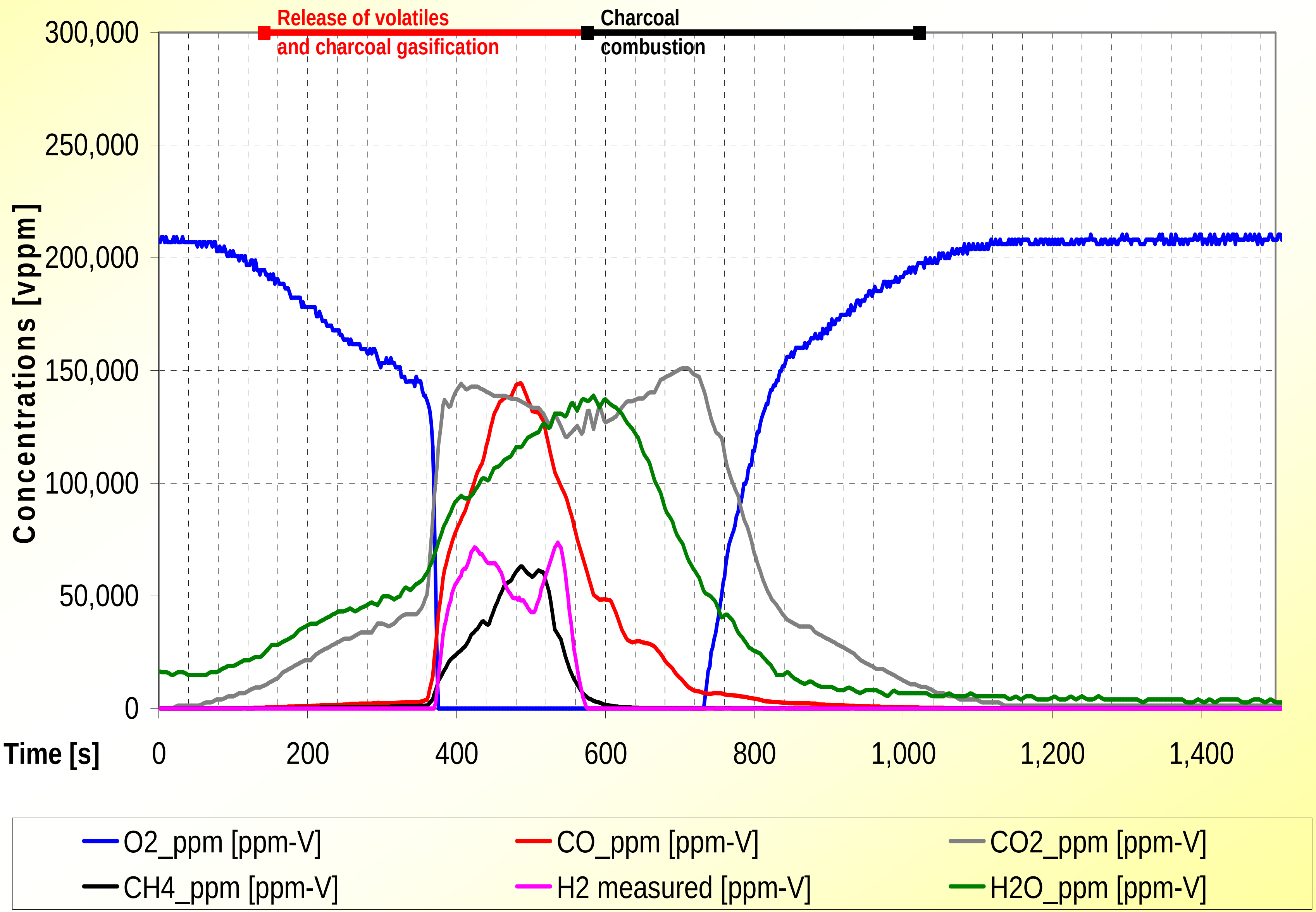
# Beech woodchips (example) – mass loss over time



# Beech woodchips (example) – flue gas species



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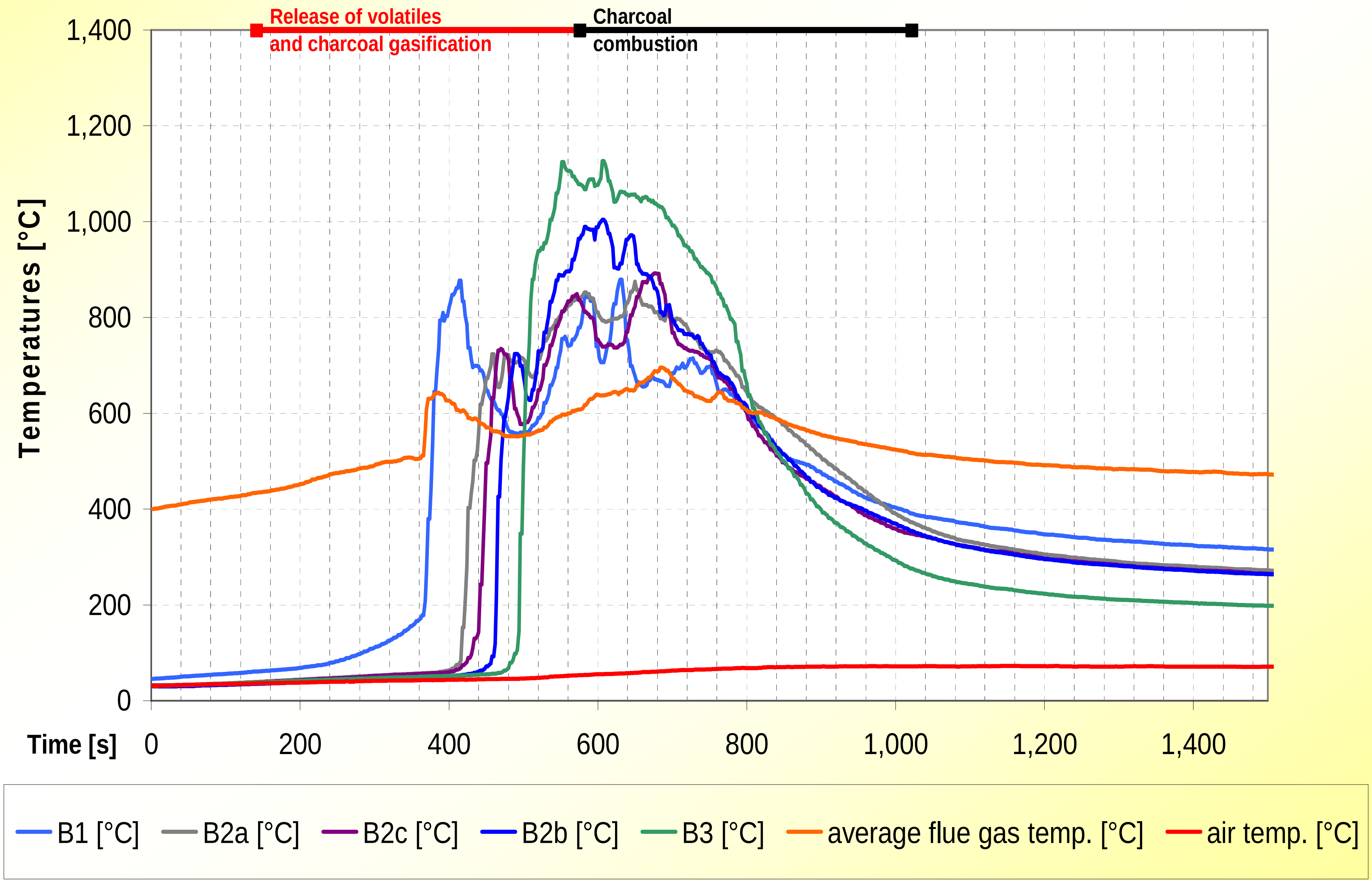
# Beech woodchips (example) – bed and gas temperatures




Average flue gas temperature: measured above the fuel bed before reactor outlet

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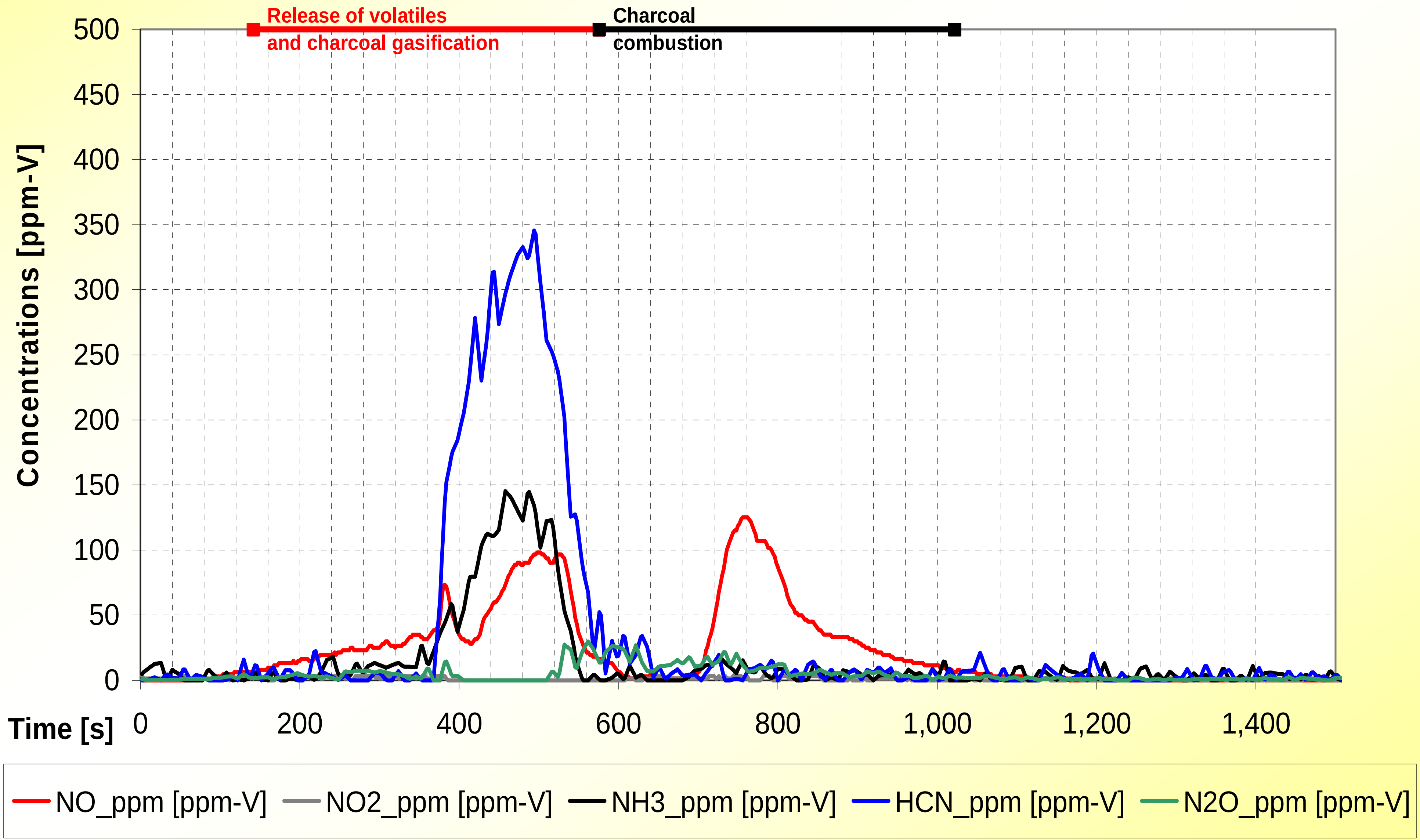
# Beech woodchips (example) – $NO_x$ precursors



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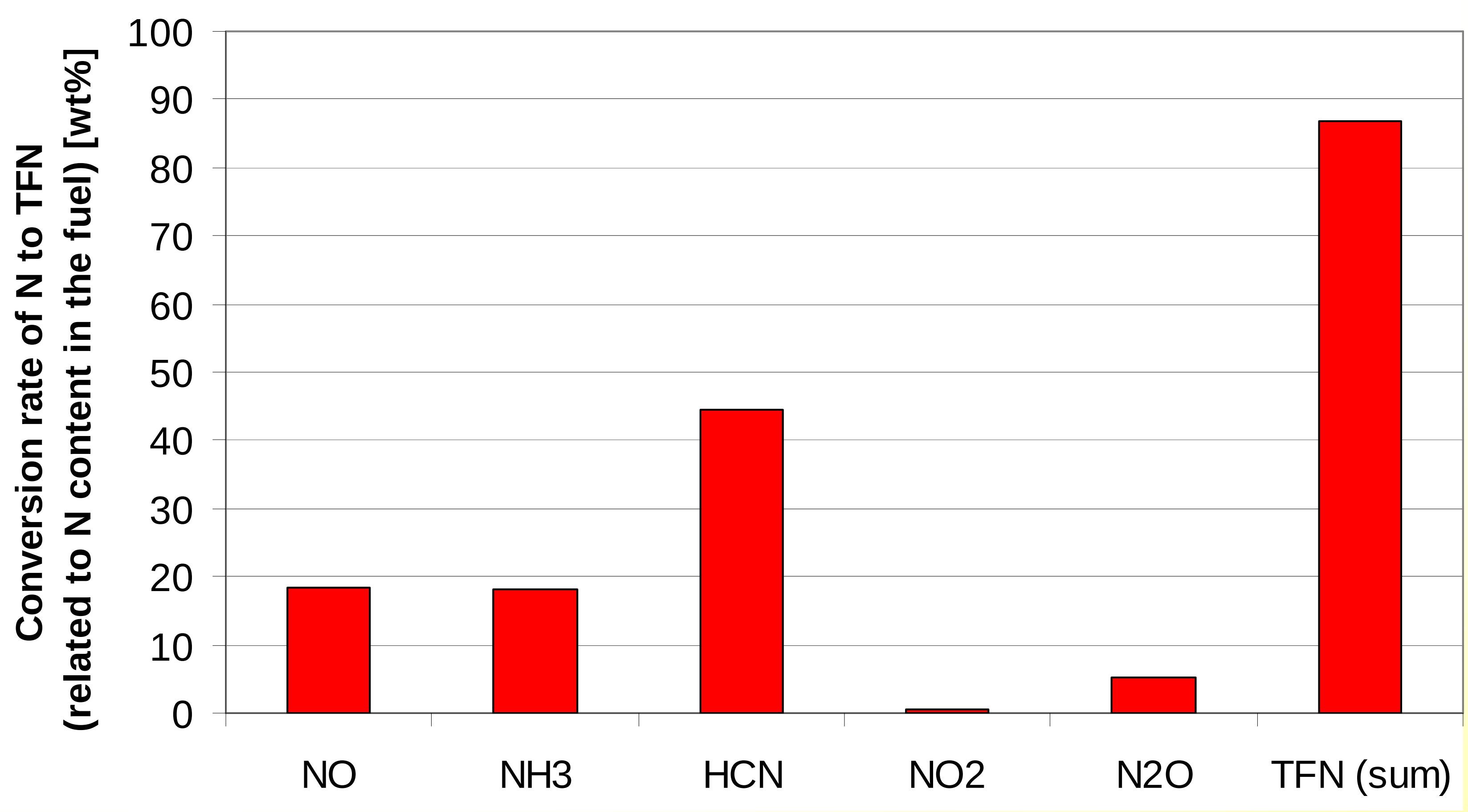
# Beech woodchips (example) – conversion of fuel N to TFN




$$\textit{conversion rate}_{N,F} = \frac{m_{N,J}}{m_{N,F}} \cdot 100\%$$

J ... N- Species (NO, $NH_3$, HCN, $NO_2$, $N_2O$)
$m_{N,J}$ … mass of N in release fraction J [g]
$m_{N,F}$ … mass of N in the fuel sample [g]



TFN ...Total Fixed Nitrogen (sum of: NO, $NH_3$, HCN, $NO_2$, $N_2O$)

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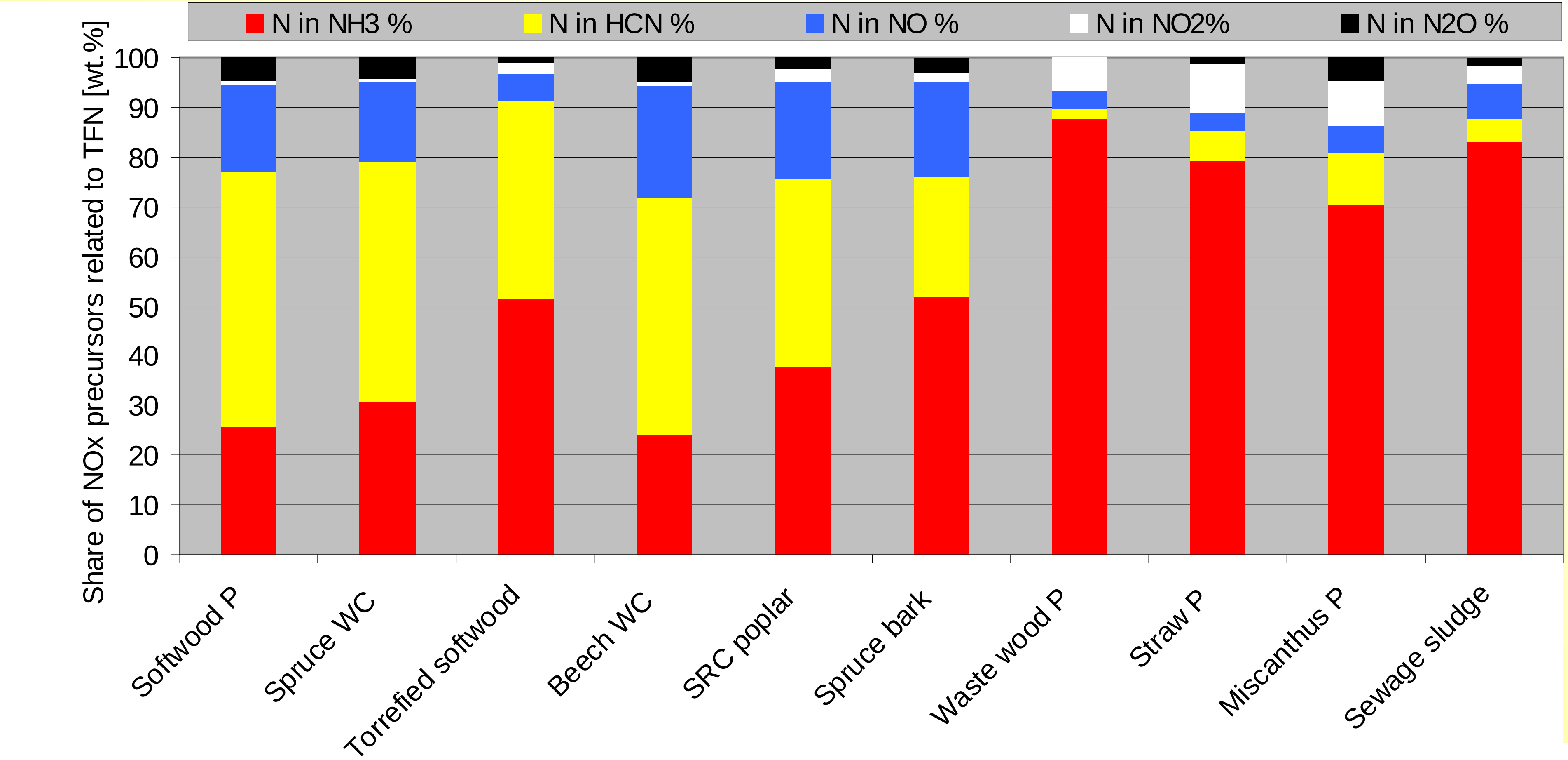
# Release of NOx precursors (I) - share of N species on TFN




$$\text{share of } NO_x \text{ precursors}_{N,TFN} = \frac{m_{N,J}}{m_{N,TFN}} \cdot 100\%$$

J ... N-species (NO, $NH_3$, HCN, $NO_2$, $N_2O$)
$m_{N,J}$ ... mass of N in released fraction [g]
$m_{N,TFN}$ ... sum of all five $m_{N,J}$ [g]

P ... pellets, WC ... woodchips
TFN ... Total Fixed Nitrogen (sum of: NO, $NH_3$, HCN, $NO_2$, $N_2O$)

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# Release of $NO_x$ precursors (II)

## Share of $NH_3$ on total fixed nitrogen (TFN) [%]:

- **high:** 70.2 – 87.7 waste wood pellets, straw pellets, Miscanthus pellets, sewage sludge
- **medium:** 37.7 – 51.9 torrefied softwood, SRC poplar, spruce bark
- **low:** 24.2 – 30.7 softwood pellets, spruce woodchips, beech woodchips

## Share of HCN on total fixed nitrogen (TFN) [%]:

- **high:** 47.6 – 51.1 softwood pellets, spruce woodchips, beech woodchips
- **medium:** 24.1 - 39.6 torrefied softwood, SRC poplar, spruce bark
- **low:** 1.8 – 10.7 waste wood pellets, straw pellets, Miscanthus pellets, sewage sludge

## Share of NO on total fixed nitrogen (TFN) [%]:

- **medium:** 16.1 – 22.7 wood fuels
- **low:** 3.5 - 6.9 waste wood pellets, straw pellets, Miscanthus pellets, sewage sludge, torrefied softwood
- During charcoal combustion NO formation clearly dominates


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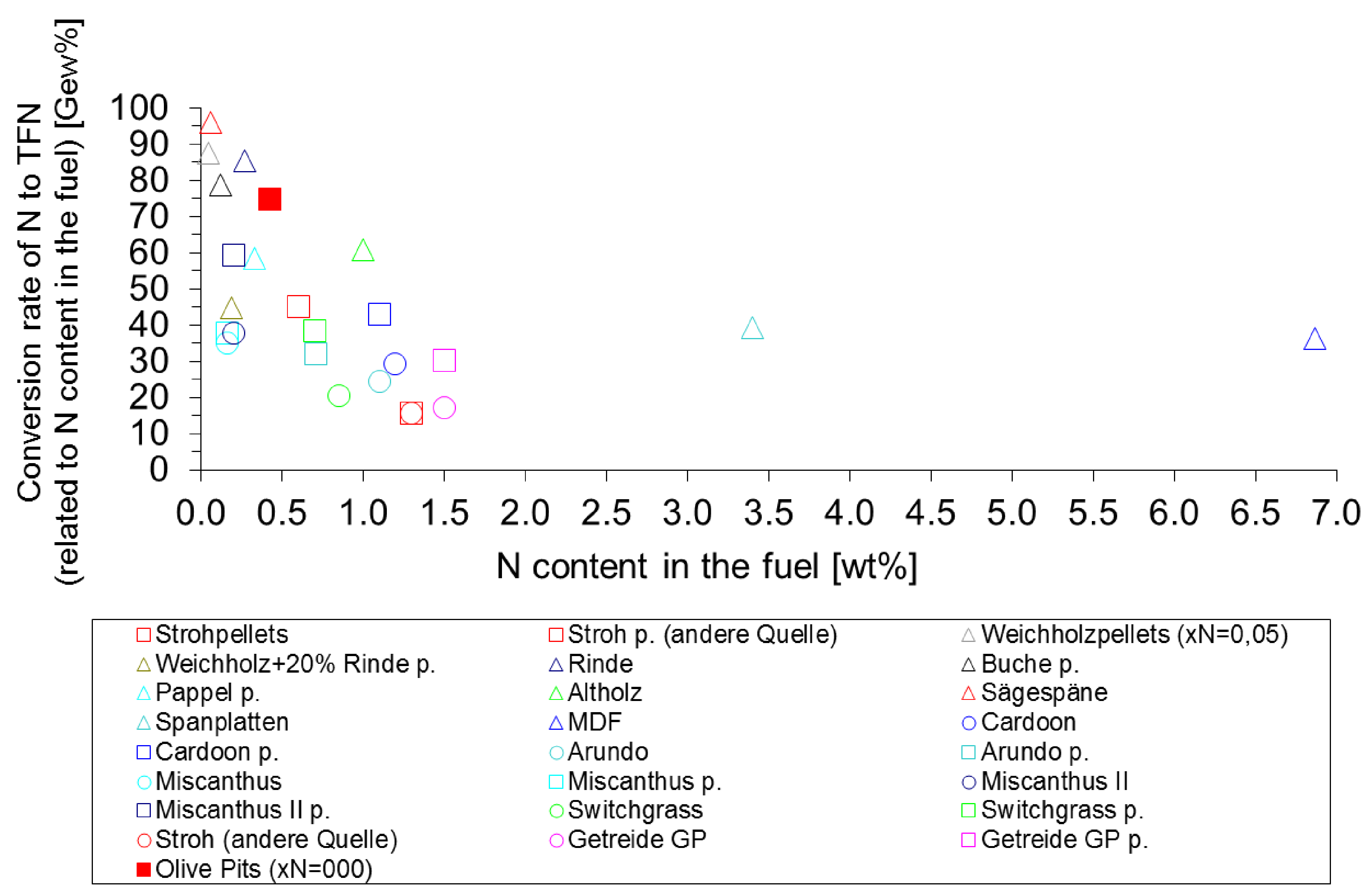
# Conversion rate of N to TFN versus N content of the fuel



# CFD simulations of $NO_x$ emissions

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# CFD simulation of $NO_x$ formation – model overview

- Extension of an empirical fixed bed model for solid biomass conversion on the grate by the relevant $NO_x$ precursor species NO, $NH_3$ und HCN or utilisation of the tar conversion model in product gas burners
- Eddy Dissipation Concept
- Detailed kinetics (Kilpinen 92) and reduced kinetics mechanism (Kilpinen 97-Skeletal)
- ISAT (In-Situ Adaptive Tabulation) algorithm for the tabulation of reaction kinetics during run-time (for the reduction of calculation time)
- Cell clustering algorithm for further calculation time reduction
- Appropriate CFD-based NOx formation model developed by BIOS in cooperation with the Graz University of Technology

ZAHIROVIC Selma, 2008: CFD analysis of gas phase combustion and $NO_x$-formation in biomass packed-bed furnaces – a contribution towards quantitative prediction of CO and $NO_x$ emissions, PhD Thesis, Institute for Process Engineering, Graz University of Technology, Austria

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# CFD simulation of $NO_x$ formation – global kinetics vs. detailled kinetics

- **Global reaction kinetics coupled with EDM**
  **→ unrealistic results**
- **Detailed reaction kinetics coupled with EDC**
  **→ good results but long calculation time**
  **Usage of reduced reaction mechanisms is necessary**

| Mechanism | Calculation model | Calculation time | Concentrations in flue gas at boiler exit | |
|---|---|---|---|---|
| | | | $NO_x$ | $NH_3$ |
| | | [h] | [ppmv] | [ppmv] |
| Measurement | | | 264 | 0 |
| De Soete | EDM | 1-2 | 203 | 1977 |
| Brink / Kilpinen | EDM | 1-2 | 637 | 0 |
| Kilpinen92 | EDC | 350 | 286 | 0 |

# CFD simulation of $NO_x$ formation – Scope of work

- 3D CFD $NO_x$ formation model (postprocessor) including detailed reaction kinetics for biomass grate furnaces
  - must be applicable to engineering problems
  - with reasonable accuracy
  - with reasonable calculation time
- Application of the CFD $NO_x$ postprocessor
  - Simulation of a pilot-scale biomass grate furnace and comparison with measurement data taken during test runs

# CFD models

## Modelling of turbulent reactive flow – basic combustion simulation

- **Turbulence** — **Realizable k-ε model**
- **Gas phase combustion** — **Eddy Dissipation model ($A_{mag}$ = 0.6) / global methane 3-step mechanism ($CH_4$, $CO$, $CO_2$, $H_2$, $H_2O$ und $O_2$)**
- **Radiation** — **Discrete Ordinates model**

## Modelling of $NO_x$ formation – postprocessing mode

- **Eddy Dissipation Concept (EDC)**
- **reduced „skeletal Kilpinen97“ reaction mechanism (28 species, 104 reactions)**
- **ISAT (In-Situ Adaptive Tabulation) algorithm for reaction kinetics**

ZAHIROVIĆ, 2008: CFD analysis of gas phase combustion and $NO_x$ formation in biomass packed-bed furnances, PhD Thesis
ZAHIROVIĆ et al., 2011: Validation of flow simulation and gas combustion sub-models for CFD-based prediction of $NO_x$ formation in biomass grate furnaces. In: Combustion Theory and Modelling (2011), Vol. No. 15, Issue No. 1, pp. 61-87

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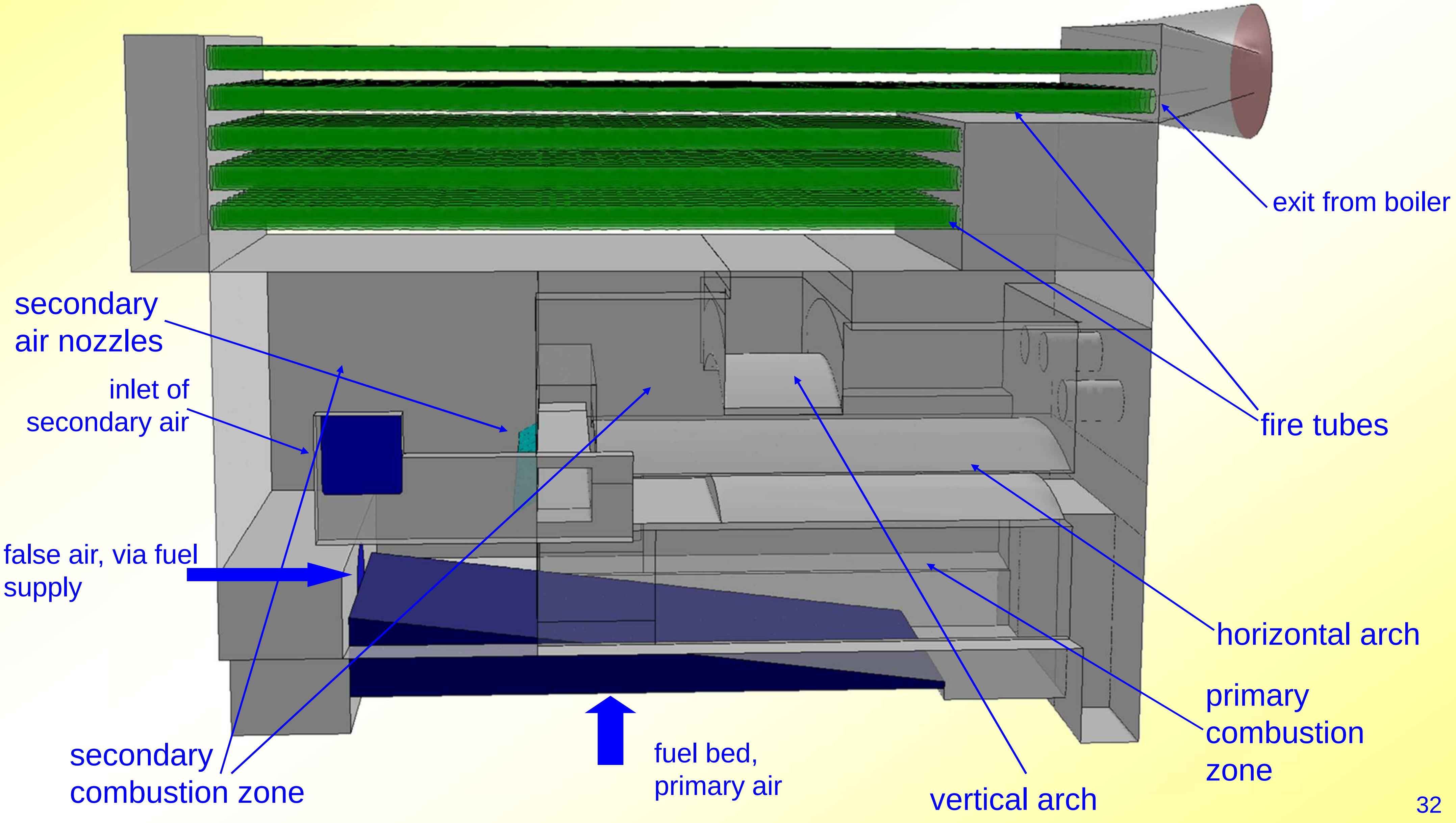
# CFD model geometry basic variant



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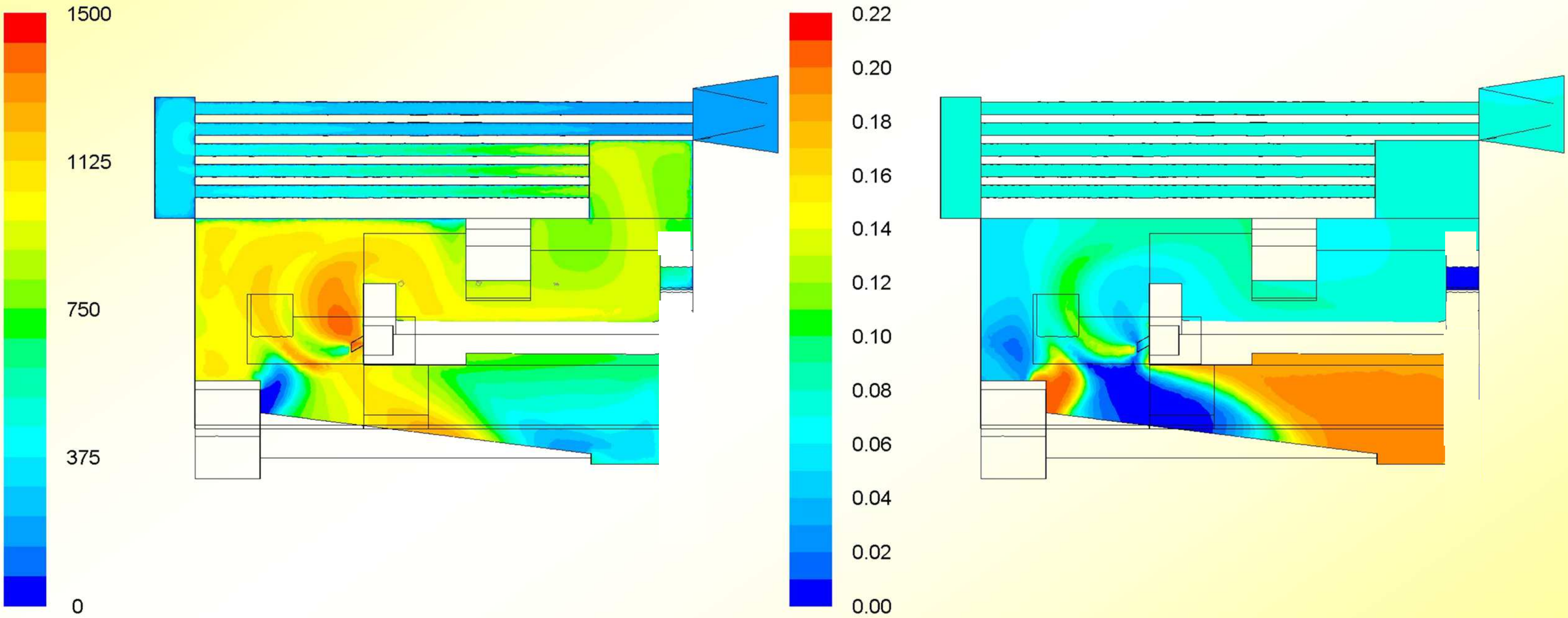
# Basic operating conditions – chemical composition of grass pellets

| Parameter | Unit | Grass pellets basic |
|---|---|---|
| C | [wt.% (d.b.)] | 48.17 |
| H | [wt.% (d.b.)] | 6.82 |
| O | [wt.% (d.b.)] | 31.83 |
| N | [wt.% (d.b.)] | 5.77 |
| S | [wt.% (d.b.)] | 0.69 |
| ash | [wt.% (d.b.)] | 6.72 |
| moisture | [wt.% (w.b.)] | 10.81 |
| GCV (analysed) | [MJ/kg (d.b.)] | 21.20 |
| GCV (Gaur) | [MJ/kg (d.b.)] | 21.40 |
| NCV | [MJ/kg (w.b.)] | 17.30 |

# Basic operating data

| Parameter | Unit | Grass pellets basic |
|---|---|---|
| Adiabatic flue gas temperature | [°C] | 1,361 |
| Fuel power (related to NCV) | [kW] | 432 |
| Flue gas in combustion chamber - total | [kg/h] | 949 |
| - Flue gas release from fuel | [kg/h] | 85 |
| - Combustion air - total | [kg/h] | 864 |
| Primary air (below grate) | [kg/h] | 403 |
| Secondary air (nozzles) | [kg/h] | 461 |
| recirculated flue gas | [kg/h] | - |
| Stoichiometric air ratio – fuel bed | [-] | 0.84 |
| Total stoichiometric air ratio | [-] | 1.67 |
| O2 fraction at combustion chamber outlet, dry | [Vol% (d.b.)] | 8.4 |

# Results of basic analysis – temperatures and $O_2$ concentrations




**Iso-surfaces of temperatures [°C] (left) and $O_2$ concentrations [m³ $O_2$/ m³ wet flue gas] (right) in the symmetry plane of the combustion chamber and the boiler**

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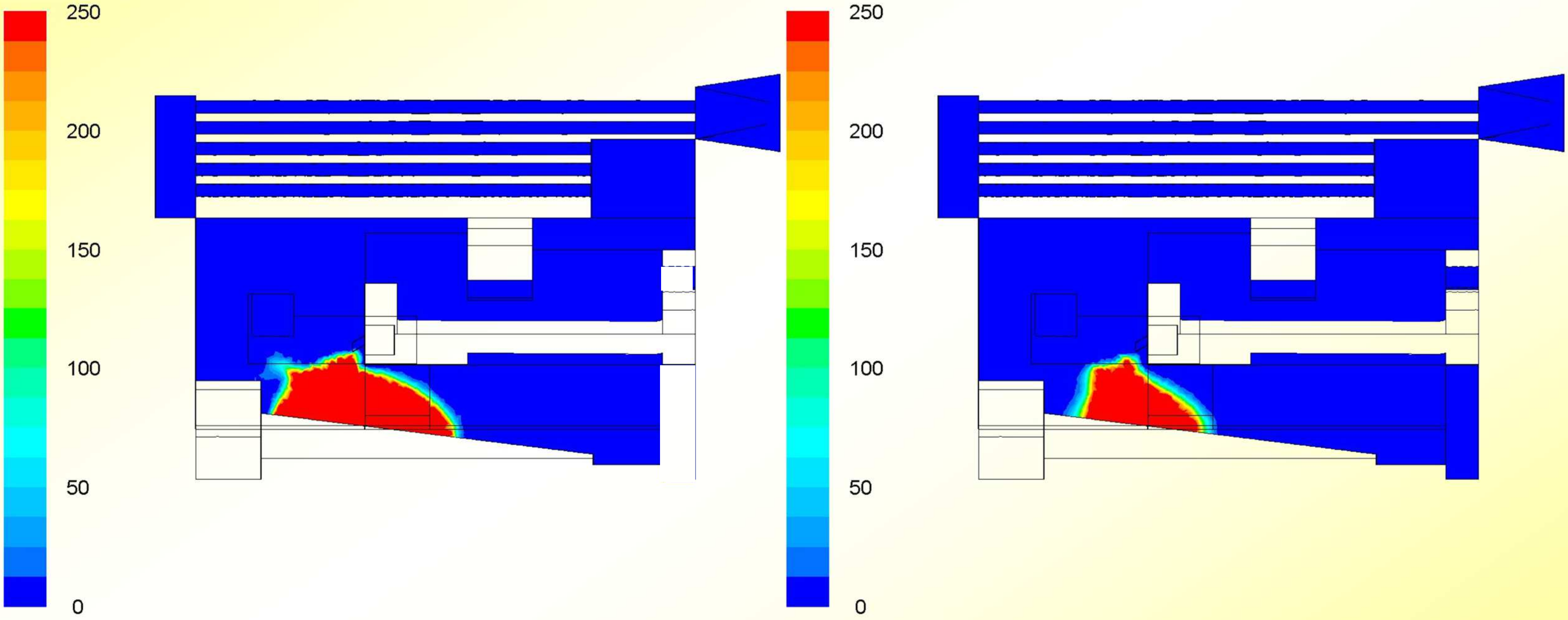
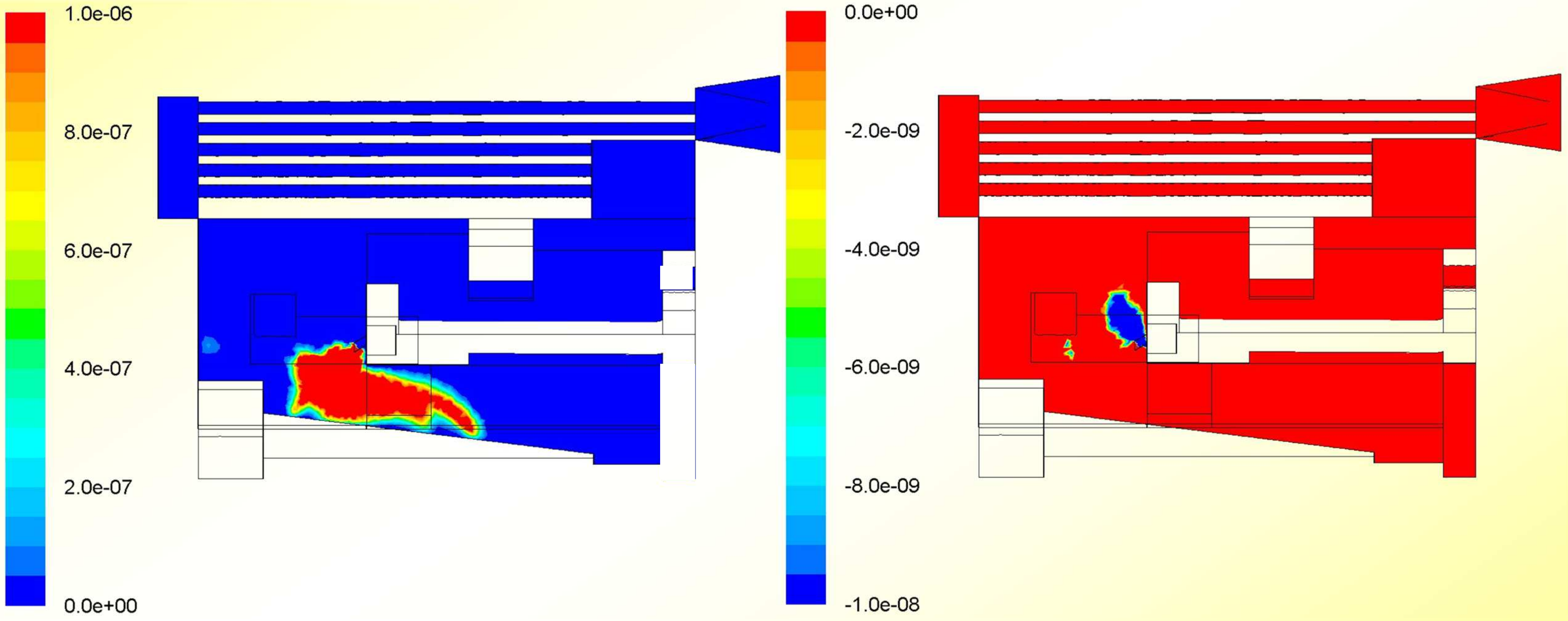
# Results of basic analysis – $NH_3$ and HCN concentrations




**Iso-surfaces of $NH_3$ concentrations [ppmv w.b.] (left) and HCN concentrations [ppmv w.b.] (right) in the symmetry plane of the combustion chamber and the boiler**

# Results of basic analysis – rates of formation of $N_2$ from NO and of NO from $N_2$




**Iso-surfaces of the reaction rates [kmol/($m^3$*s)] of the reaction N + NO → $N_2$ + O for the reduction to $N_2$ (left) and of the reaction N + NO ← $N_2$ + O for the formation of NO from $N_2$ (right) in the symmetry plane of the combustion chamber and the boiler**

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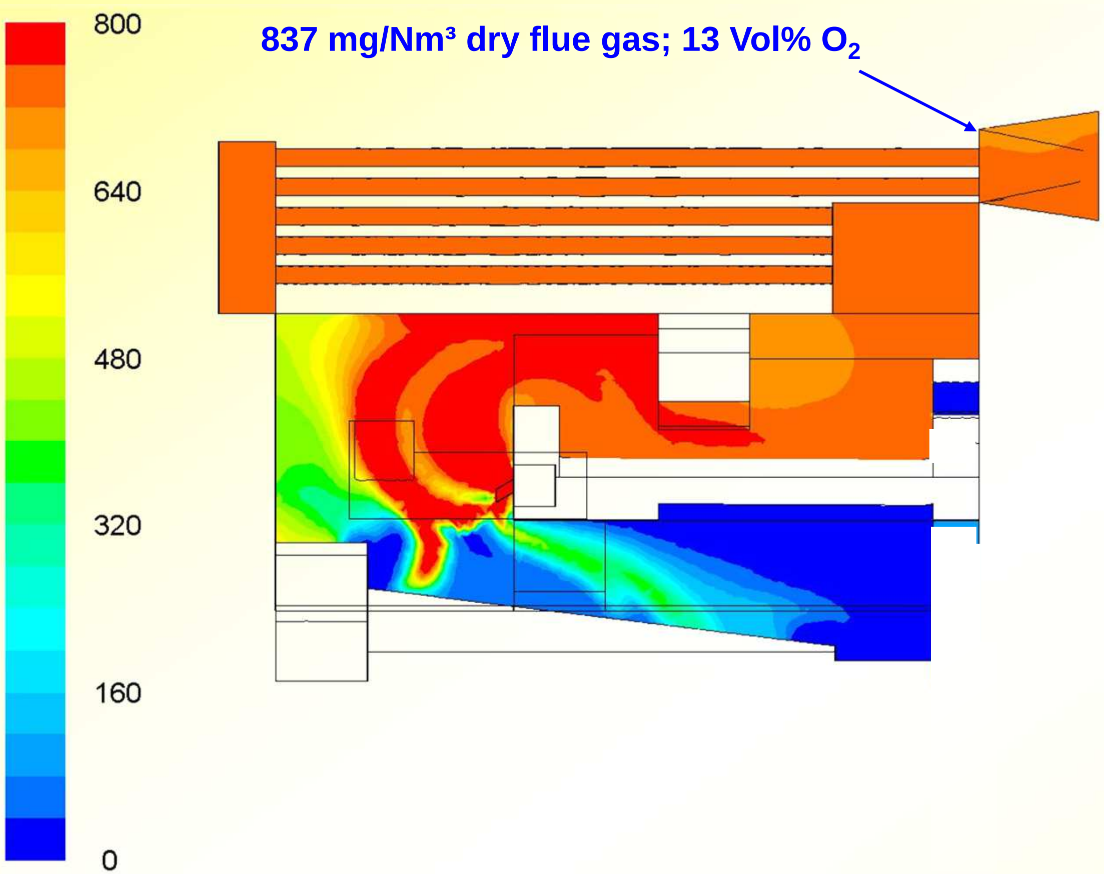
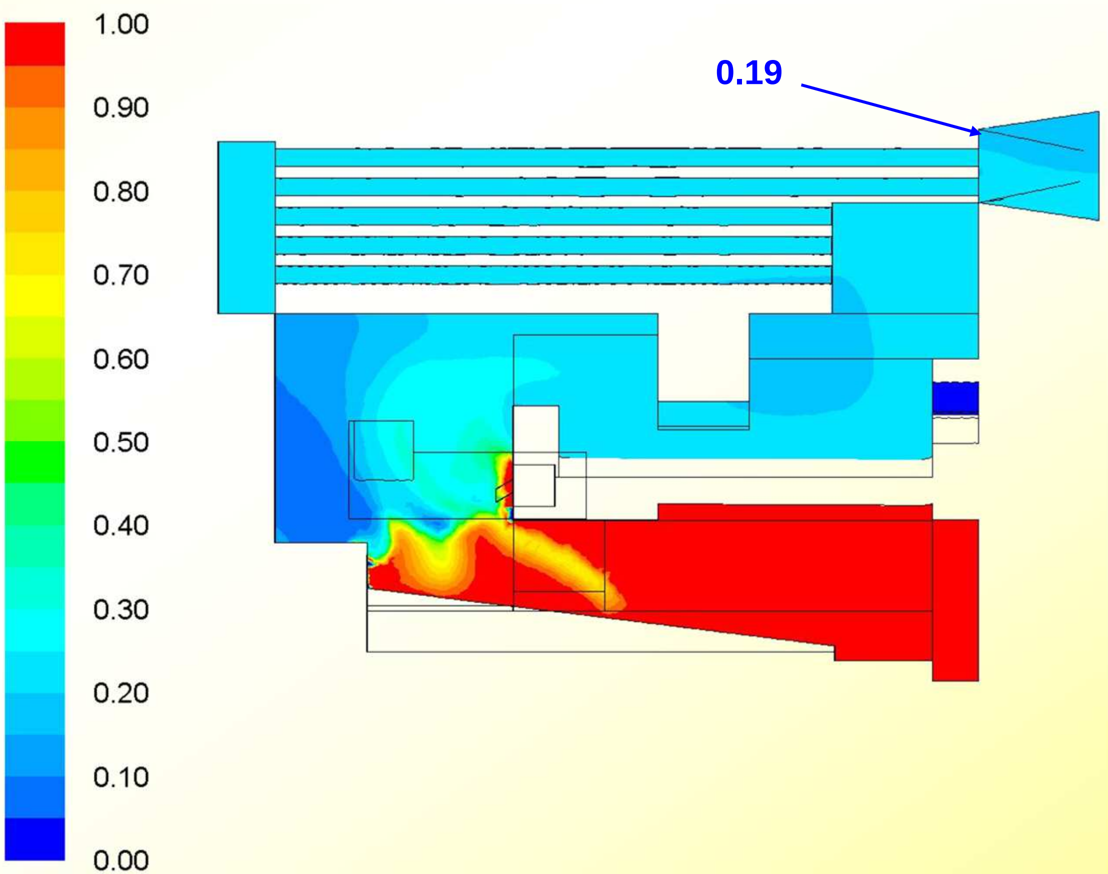
# Results of basic analysis – NOx concentrations and TFN/TFN$_{in}$ ratio




**Iso-surfaces of $NO_x$ concentrations [ppmv w. b.] in the symmetry plane of the combustion chamber and the boiler**

explanations: $NO_x$ concentrations as sum of NO, $NO_2$ and $N_2O$ concentrations, all in [ppmv w. b.]

**Iso-surfaces of local TFN/TFN$_{in}$ ratios in the symmetry plane of the combustion chamber and the boiler**

explanation: all data taken from reactor experiments with lab-scale pot furnace;
TFN … mass of all N-moles contained in NO, $NH_3$, $NO_2$, HCN und $N_2O$, released from the fuel bed

# Results of basic analysis – evaluation

## Evaluation of basic analysis:

- small primary combustion zone (small flue gas residence time for reduction)
- thermal $NO_x$ (high local flue gas temperatures)

## Measures taken for optimization:

- new position of secondary air nozzles
- flue gas recirculation (temperature control)

# Basic and optimized variant – operating data

| **Parameter** | **Unit** | **Grass pellets basic** | **Grass pellets optimised** |
|---|---|---|---|
| Adiabatic flue gas temperature | [°C] | 1,361 | 1,042 |
| Fuel power (related to NCV) | [kW] | 432 | 370 |
| Flue gas in combustion chamber - total | [kg/h] | 949 | 1,126 |
| - Flue gas release from fuel | [kg/h] | 85 | 72 |
| - Combustion air - total | [kg/h] | 864 | 753 |
| Primary air (below grate) | [kg/h] | 403 | 362 |
| Secondary air (nozzles) | [kg/h] | 461 | 391 |
| recirculated flue gas | [kg/h] | - | 301 |
| Stoichiometric air ratio – fuel bed | [-] | 0.84 | 0.79 |
| Total stoichiometric air ratio | [-] | 1.67 | 1.64 |
| Effective stoichiometric air ratio on grate(1) | [-] | | 0.91 |
| Effective stoichiometric air ratio in primary combustion zone(2) | [-] | | 1.03 |
| Ratio of recirculated flue gas below grate | [-] | - | 0.52 |
| Flue gas recirculation ratio | [-] | - | 0.27 |
| O2 fraction at combustion chamber outlet, dry | [Vol% (d.b.)] | 8.4 | 8.3 |

(1) stoichiometric ratio including primary air and recirculated flue gas below the grate

(2) stoichiometric ratio including primary air and recirculated flue gas below the grate and through the nozzles

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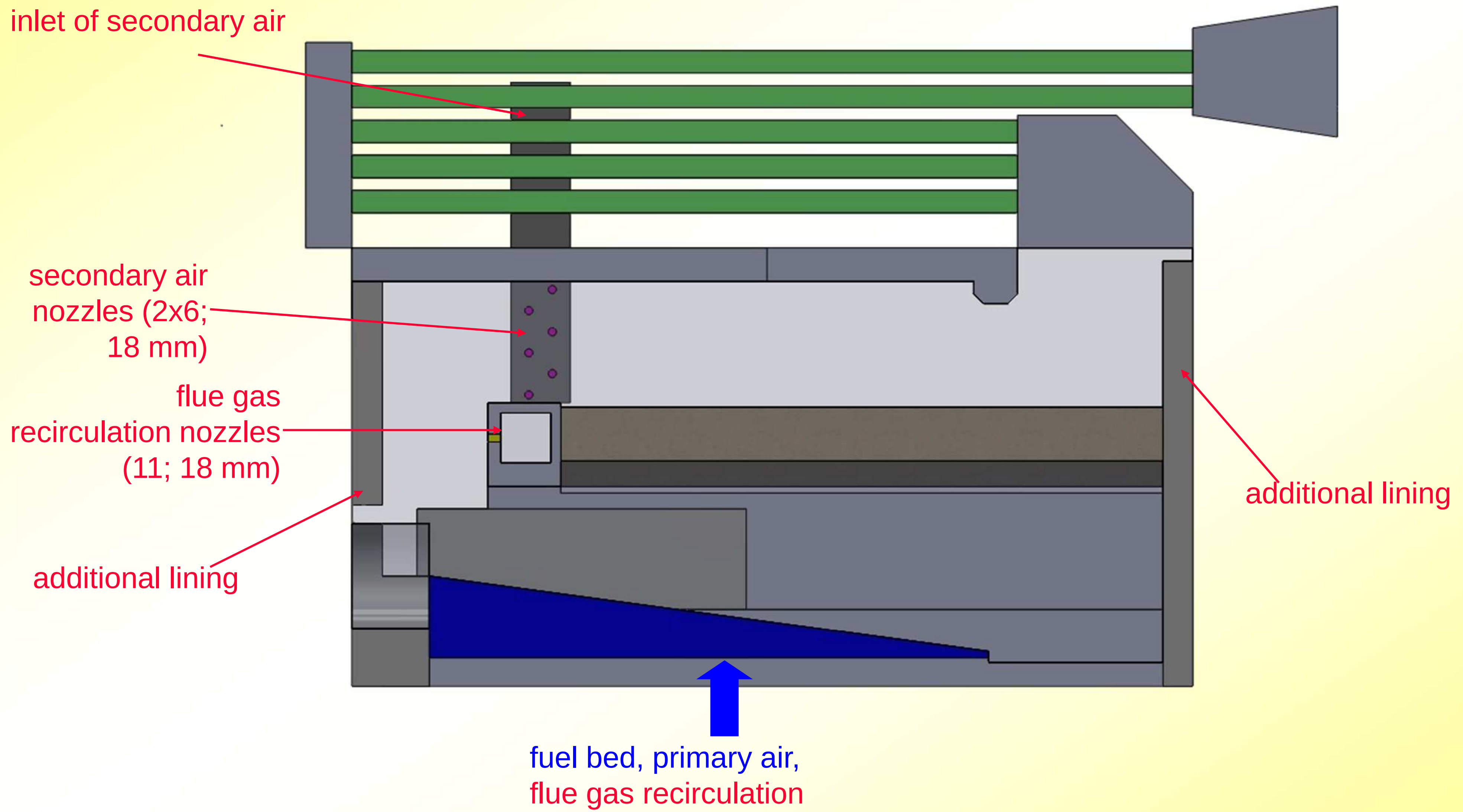
# CFD model geometry optimised variant



# Results of optimization – $NO_x$ concentrations

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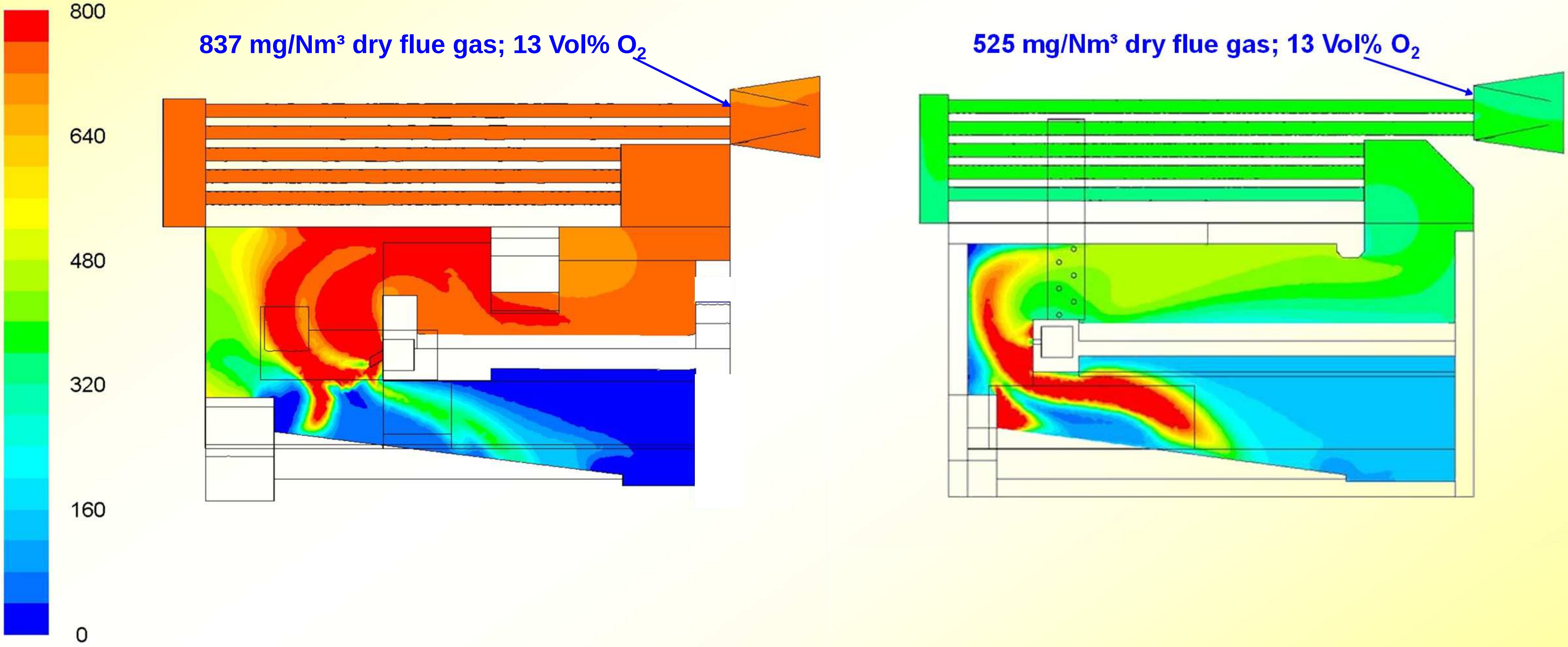
**grass pellets**
**basic geometry**
**basic operating conditions**

**grass pellets**
**optimized geometry**
**optimized operating conditions**




**Iso-surfaces of $NO_x$ concentrations [ppmv w. b.] in the symmetry plane of the combustion chamber and the boiler**

**explanations: $NO_x$ concentrations as sum of NO, $NO_2$ and $N_2O$ concentrations, all in [ppmv w. b.]**

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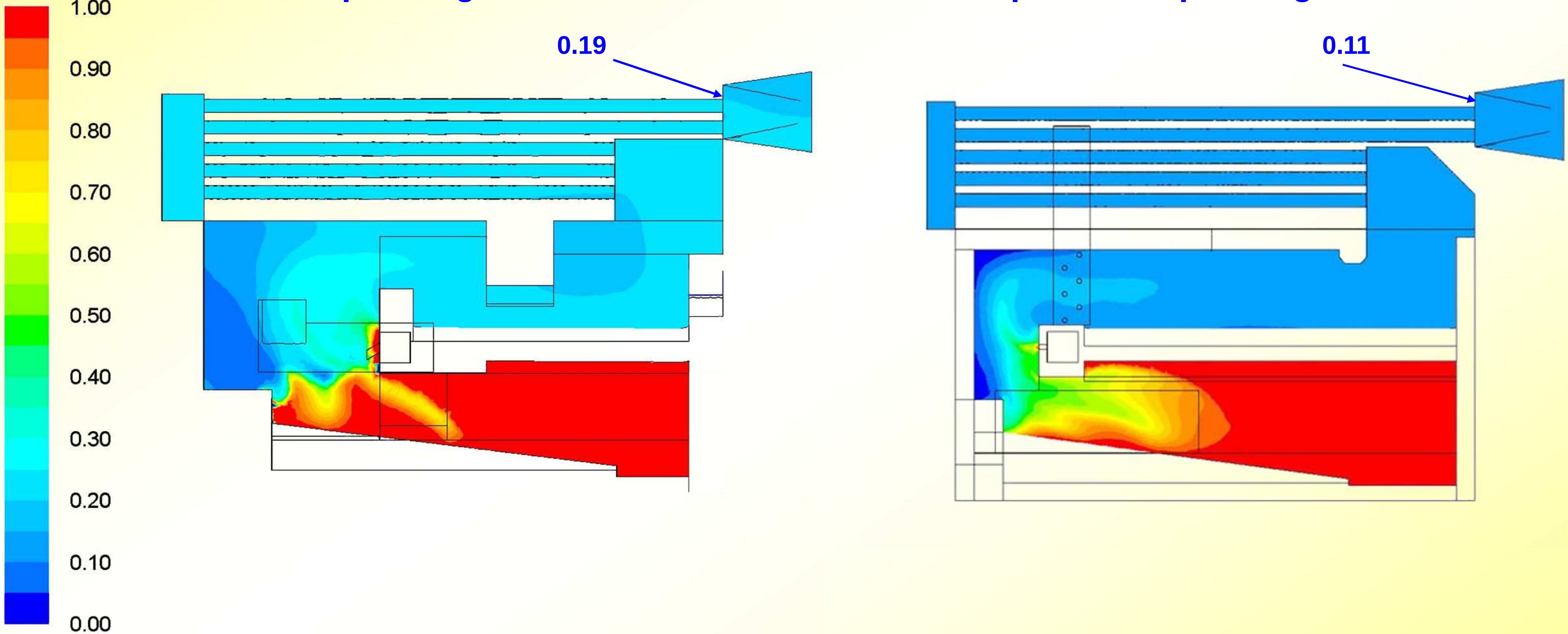
# Results of optimization – TFN/TFN$_{in}$ ratios

**grass pellets**
**basic geometry**
**basic operating conditions**

**grass pellets**
**optimized geometry**
**optimized operating conditions**




**Iso-surfaces of local TFN/TFN$_{in}$ ratios in the symmetry plane of the combustion chamber and the boiler**

**<u>explanation</u>: TFN … mass of all N-moles contained in NO, $NH_3$, $NO_2$, HCN und $N_2O$, released from the fuel bed**

# Results of optimization – measurement compared to simulation results

| | Unit | Grass pellets optimised |
|---|---|---|
| simulated $NO_x$-emissions (calculated as $NO_2$) at boiler exit | mg $NO_x$/Nm³ dry fuel gas; 13 Vol.% O2 | 525 |
| measured $NO_x$-emissions | mg $NO_x$/Nm³ dry fuel gas; 13 Vol.% O2 | 572 |

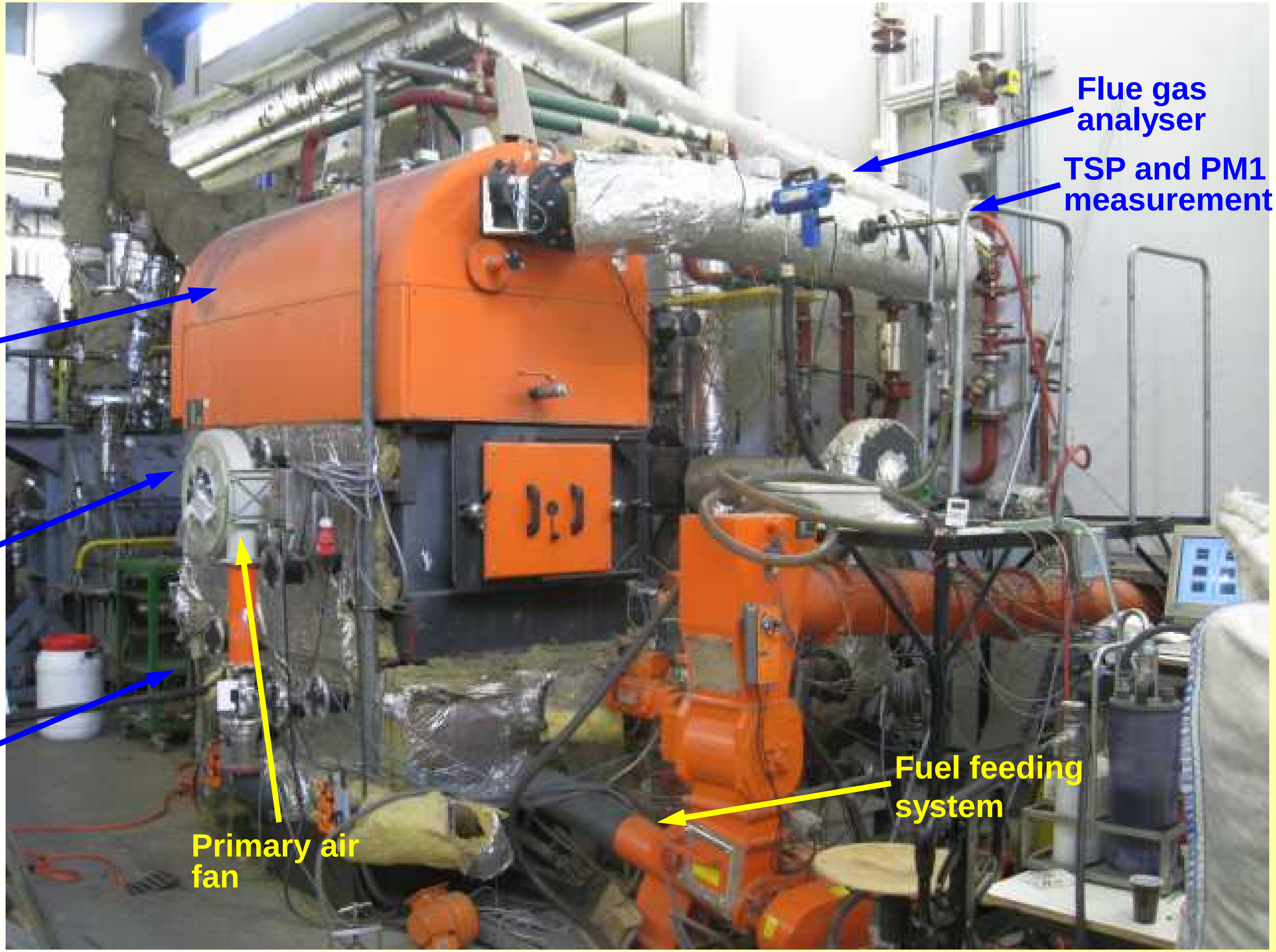
# $NO_x$ reduction by primary measures

# Project ERANET-FutureBiotec - Measurement set-up

Heat exchanger

Secondary combustion chamber

Primary combustion chamber



# General test run data

- **Average amount of false air (related to the total combustion air input): 10.1%**
- **Average boiler capacity for the test runs performed:**
  **150 kW at full load and 75 kW at partial load**
- **Average $O_2$ content in the flue gas:**
  **6.2 Vol% (dry flue gas)**
  **corresponding to a total air ratio of 1.4**
- **Average CO emissions:**
  **19 mg/Nm$^3$ (dry flue gas, 13% Vol% $O_2$**

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# Project ERANET-FutureBiotec – test programme

**Test series 1, 2, 3:**
- Side constraints: full load (150 kW), fg recirculation above grate and large PCC
- Varied parameter: primary air ratio
- Fixed parameter: temperature at PCC outlet: 900; 1,000 and 1,100 °C

**Test series 4, 5, 6:**
- Side constraints: full load (150 kW), fg recirculation below grate and large PCC
- Varied parameter: primary air ratio
- Fixed parameter: temperature at PCC outlet: 900; 1,000 and 1,100 °C

**Test series 7:**
- Side constraints: full load (150 kW), fg recirculation above grate and small PCC
- Varied parameter: primary air ratio
- Fixed parameter: temperature at PCC outlet: 1,000 °C

**Test series 8:**
- Side constraints: full load (150 kW), fg recirculation below grate and small PCC
- Varied parameter: primary air ratio
- Fixed parameter: temperature at PCC outlet: 1,000 °C

**Test series 9:**
- Side constraints: partial load (75 kW), fg recirculation above grate and large PCC
- Varied parameter: primary air ratio
- Fixed parameter: temperature at PCC outlet: 1,000 °C

fg … flue gas; PCC … primary combustion chamber

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# Project ERANET-FutureBiotec – analysis of the chipboard used

| fuel | | chipboard | chipboard | chipboard - database values | | |
|---|---|---|---|---|---|---|
| analysis-no. | | 8,673 | 9,131 | min. | max. | no. of samples |
| mc | wt% w.b. | 9.1 | 6.9 | | | |
| gross calorific value | kJ/kg d.b. | 19,500 | 19,600 | 19,600 | 19,600 | 1 |
| ac | wt% d.b. | 0.88 | 1.20 | 0.52 | 1.49 | 6 |
| ac (without TIC) | wt% d.b. | 0.75 | 1.01 | | | |
| C | wt% d.b. | 47.4 | 48.0 | 47.7 | 51.2 | 17 |
| H | wt% d.b. | 6.2 | 6.0 | 5.4 | 7.3 | 17 |
| N | wt% d.b. | 3.6 | 3.8 | 2.4 | 3.6 | 17 |
| S | mg/kg d.b. | 322.0 | 179.0 | 151.0 | 630 | 5 |
| Cl | mg/kg d.b. | 285.0 | 191.0 | 123.0 | 1,250 | 5 |
| Si | mg/kg d.b. | 788 | 1,240 | 36.3 | 1,360 | 8 |
| Ca | mg/kg d.b. | 1,770 | 2,190 | 1,197 | 3,001 | 8 |
| Mg | mg/kg d.b. | 333.0 | 434.0 | 176.0 | 310.0 | 8 |
| K | mg/kg d.b. | 600 | 698 | 527 | 980 | 8 |
| Na | mg/kg d.b. | 192.0 | 232.0 | 90.9 | 301.0 | 8 |
| P | mg/kg d.b. | 73.1 | 76.0 | 142.0 | 149.0 | 2 |
| Zn | mg/kg d.b. | 60.7 | 42.0 | 15.6 | 64.3 | 8 |
| Pb | mg/kg d.b. | 9.4 | 5.0 | 1.73 | 61.0 | 5 |

Explanations: mc ... moisture content; ac ... ash content; d.b. … dry base; w.b. … wet base; TIC … total inorganic carbon

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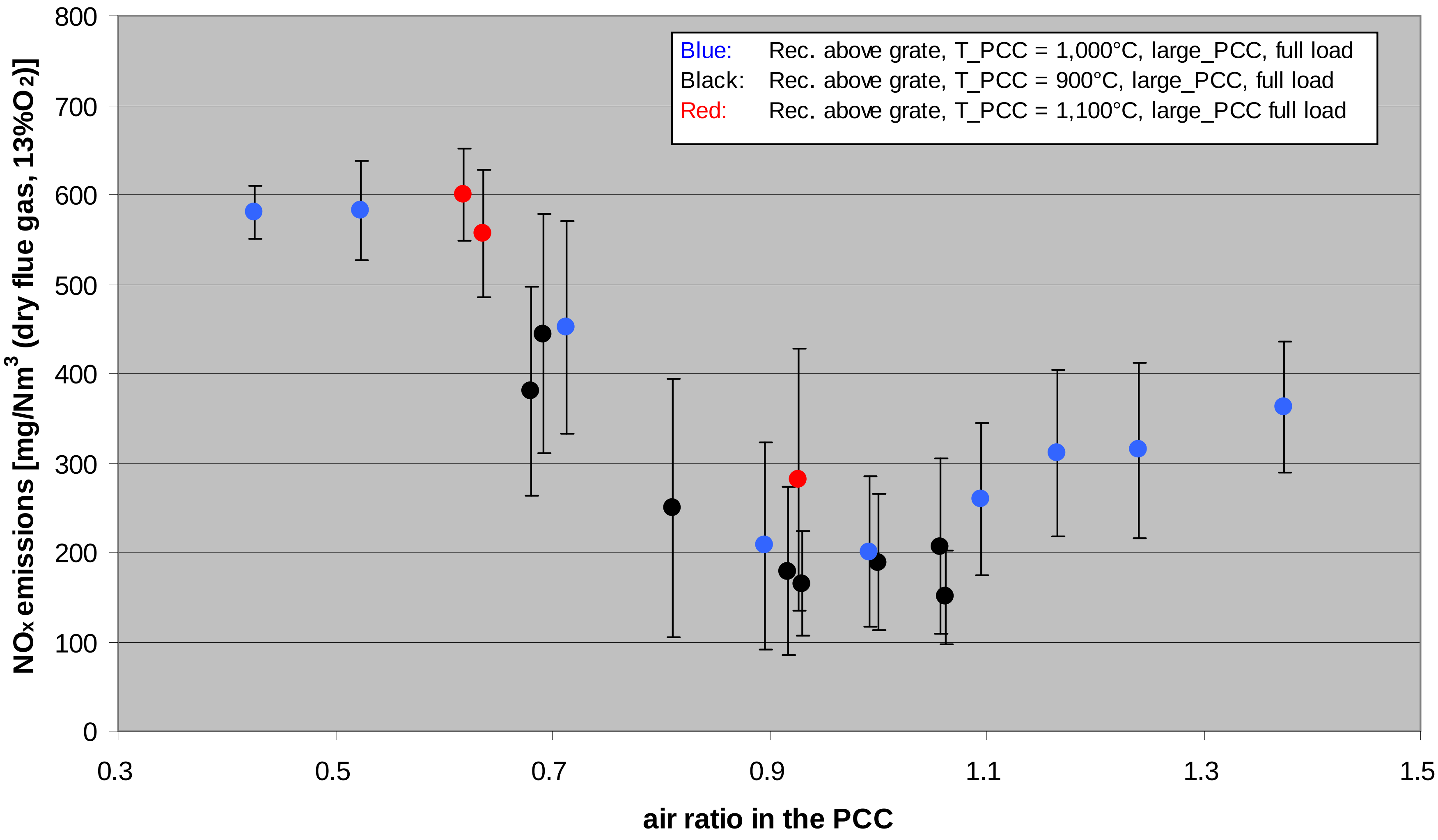
# Test runs performed with chipboard – air ratio in the PCC versus $NO_x$ emissions for varying temperatures in the PCC




Explanations: Rec … flue gas recirculation; PCC … primary combustion chamber;
T_PCC … temperature at outlet of the primary combustion chamber;

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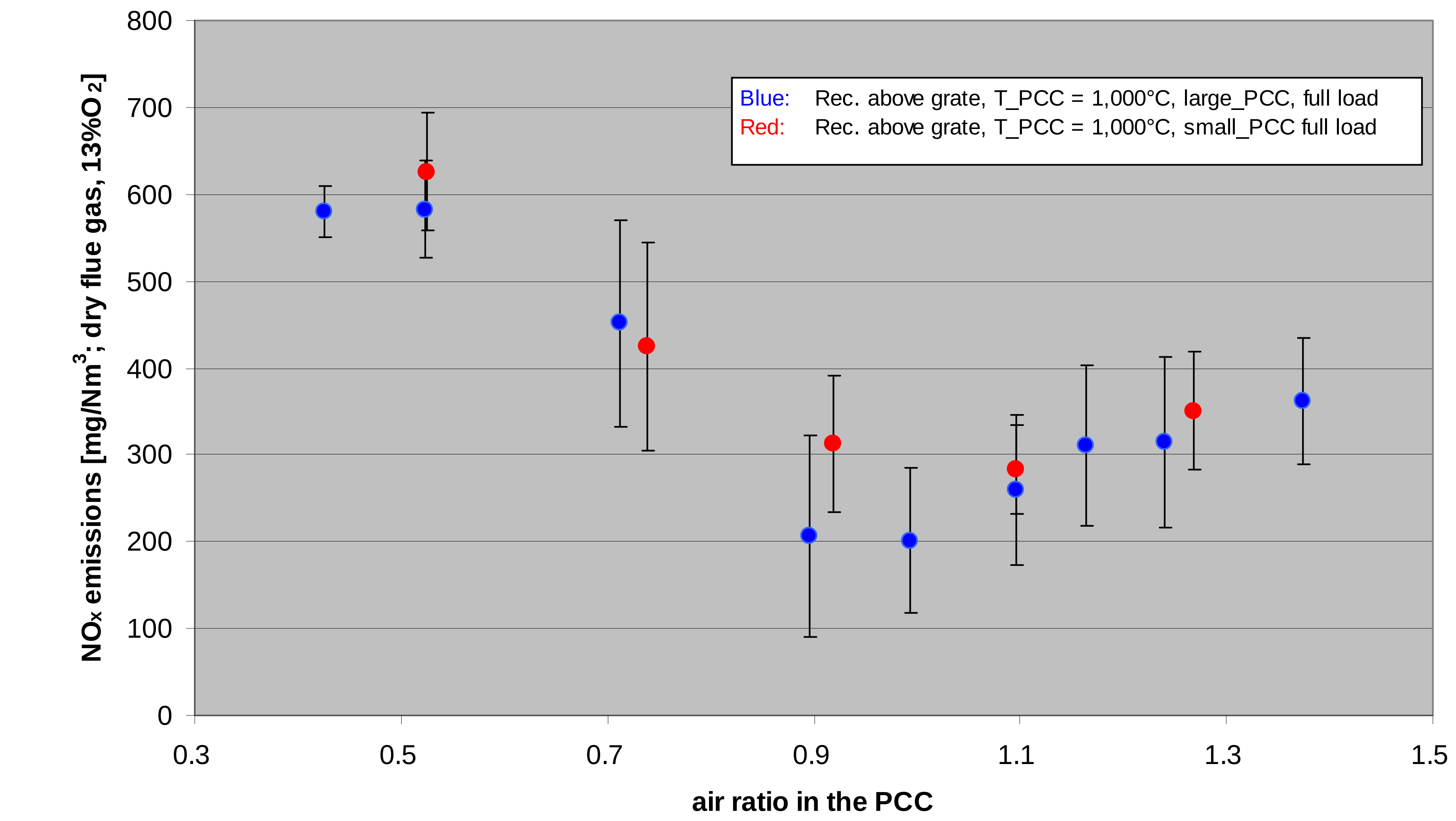
# Test runs performed with chipboard – air ratio in the PCC versus $NO_x$ emissions for varying residence time




Explanations: Rec … flue gas recirculation; PCC … primary combustion chamber;
T_PCC … temperature at outlet of the primary combustion chamber;

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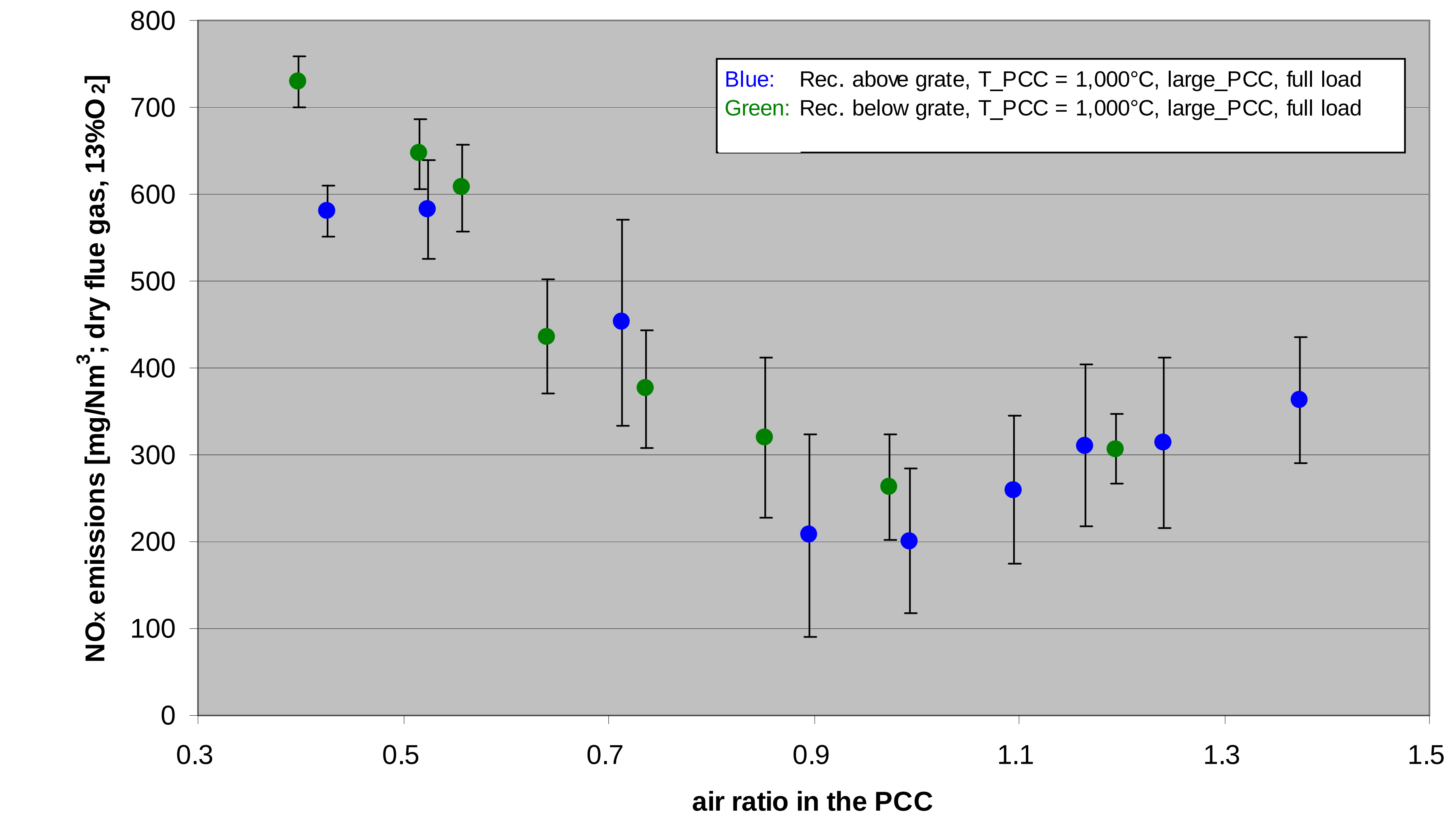
# Test runs performed with chipboard – air ratio in the PCC versus $NO_x$ emissions for different type of flue gas recirculation




Explanations: Rec … flue gas recirculation; PCC … primary combustion chamber;
T_PCC … temperature at outlet of the primary combustion chamber;

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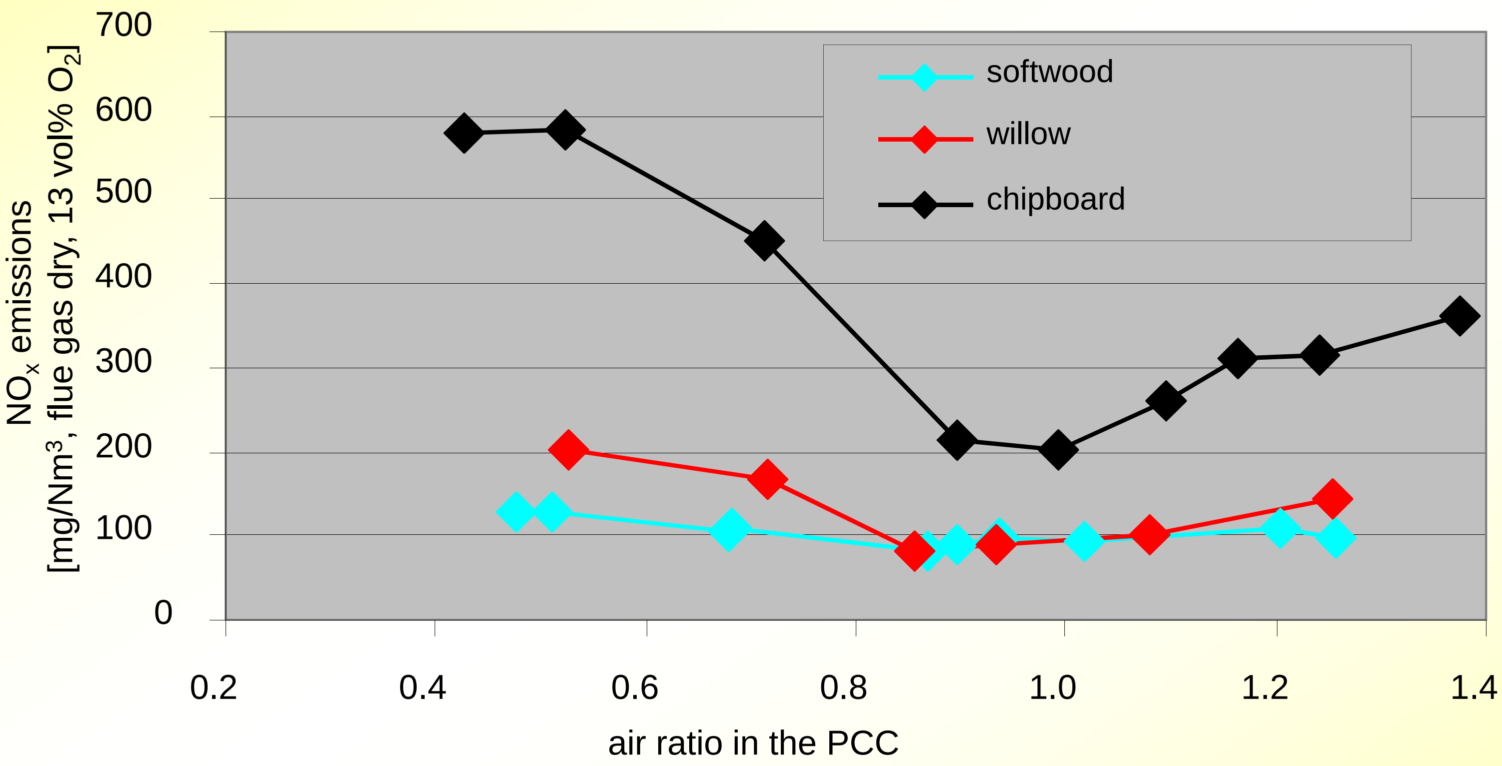
# Project ERANET-FutureBiotec – influence of air staging on $NO_x$ emissions for different fuels




$NO_x$ as $NO_2$ related to dry flue gas and 13vol% $O_2$; all measurements at full load;
PCC … primary combustion chamber
Side constraints: Rec. above grate, T_PCC = 1,000°C, large_PCC, full load

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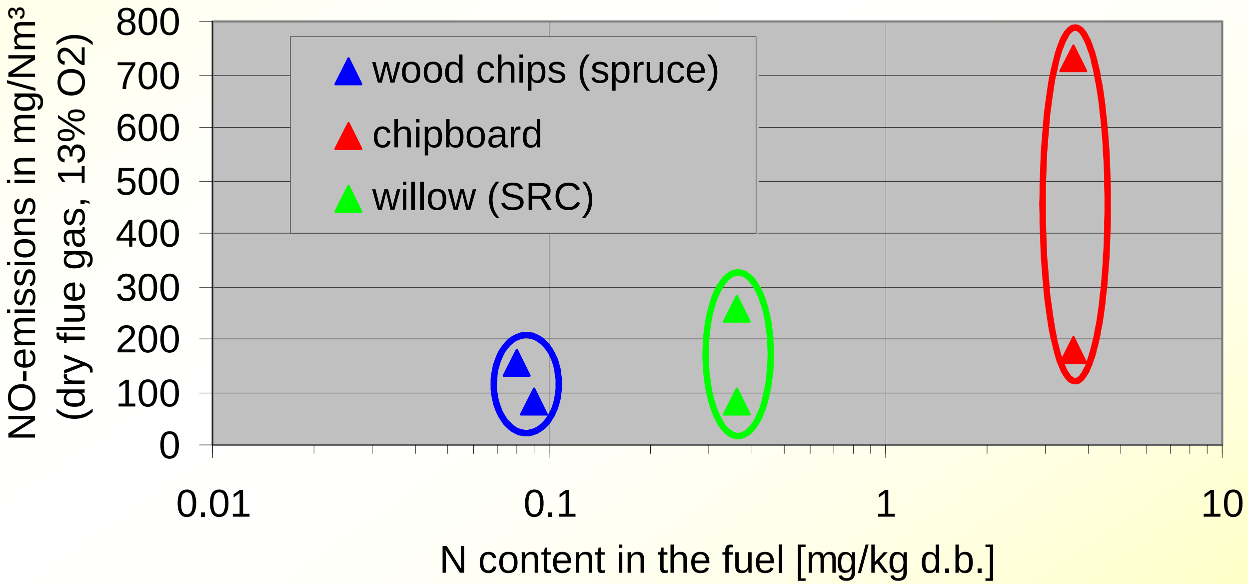
# Project ERANET-FutureBiotec – conclusions regarding $NO_x$ reduction by primary measures

- $\lambda_{PCC}$ is the most relevant influencing parameter
- technology dependent optimum of $\lambda_{PCC}$ at $\lambda_{PCC}$ <1
- the optimum $\lambda_{PCC}$ seems to be fuel independent for a certain combustion technology
- a second relevant influencing parameter is the residence time in the PCC (increasing $NO_x$ emissions with decreasing residence time)
- air staging shows a great $NO_x$ reduction potential
- The amount of false air should be minimized




Range of $NO_x$ emissions at different operation conditions

Data taken from test runs with wood chips, willow and chipboard

# $NO_x$ reduction by secondary measures

# $NO_x$-reduction by secondary measures

**If secondary measures are necessary, they should always be combined with primary measures.**

**Possible secondary measures:**

- **SNCR: selective non catalytic reduction**
  - Injection of a reducing agent (ammonia or urea) into the hot furnace
  - Temperature window: between 850 and 950°C
- **SCR: selective catalytic reduction**
  - Injection of a reducing agent into the flue gas (downstream the boiler)
  - Reducing agents:
    - ammonia (at temperatures between 220 and 270°C)
    - urea (at temperatures between 400 and 450°C)
  - Platinum, titanium or vanadium oxide based catalysts are used for SCR

**Reduction reactions**

$$4NO + 4NH_3 + O_2 \Rightarrow 4N_2 + 6H_2O$$

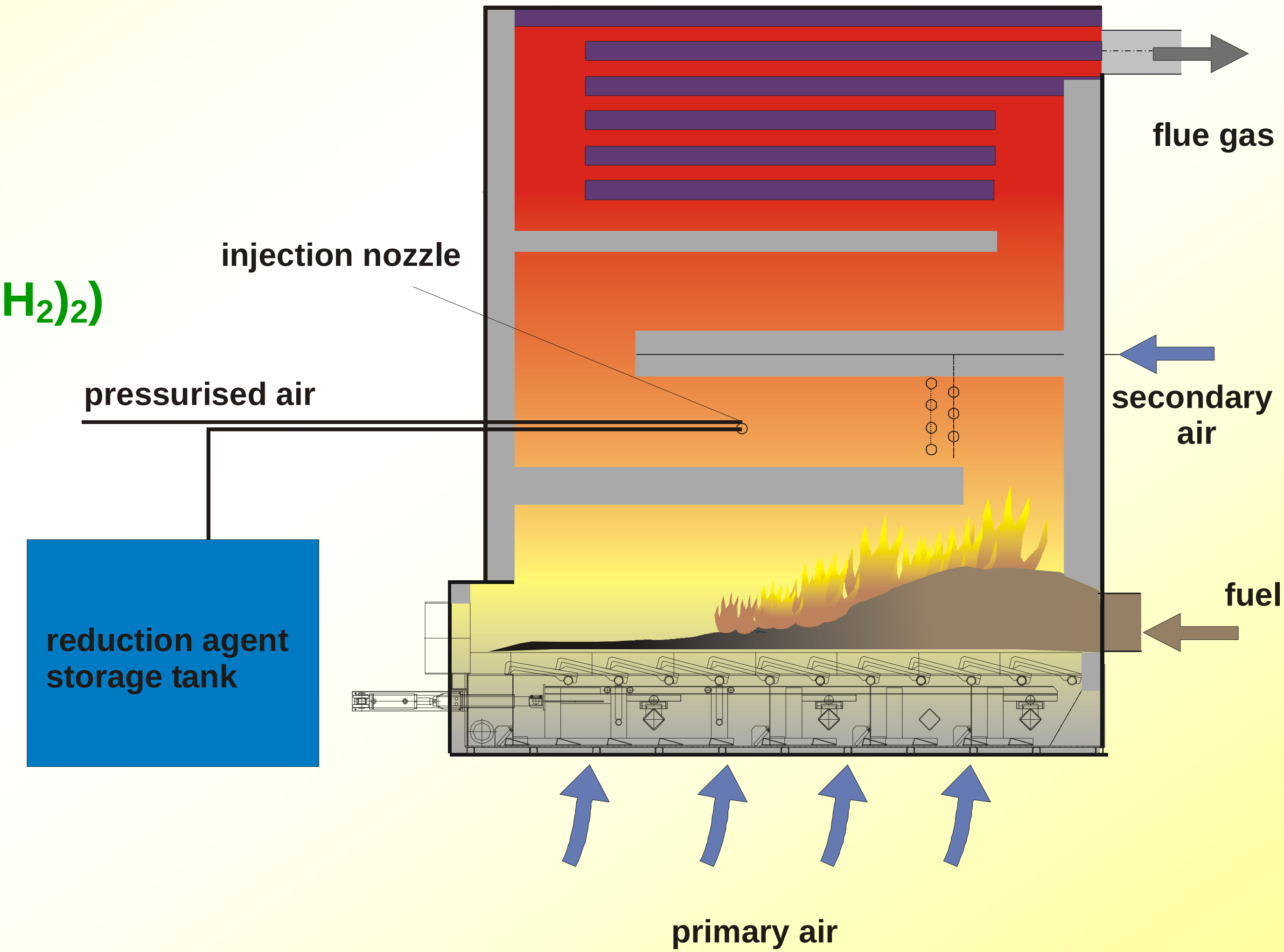
$$3NO_2 + 4NH_3 + O_2 \Rightarrow 3N_2 + 6H_2O$$

# $NO_x$-reduction by secondary measures

## SNCR process (case study grate furnace)

**Constraints:**

- **reducing agent:** ammonia ($NH_3$) or urea ($CO(NH_2)_2$)
- **stoichiometric coefficient:** about 2.2
- **residence time of the flue gas in the furnace after ammonia/urea injection:** 0.3–0.5 s
- **operation temperature:** 850-950°C
- **average $NO_x$-reduction:** 60 to 70%




- **Urea based SNCR usually increases the CO emissions by about 10 to 20 ppm**

**stoichiometric coefficient:** $NH_3/NO_x$ respectively $CO(NH_2)_2/2NO_x$

## SNCR process: costs (example):

- **Investment costs of a SNCR unit for a biomass boiler system (nominal thermal capacity of 5.2 MW):**
  **270,000 € (excl. VAT)**
  **(including filling device, storage tank (22 m³), nozzels, dosing and control unit)**

- **Operating cost SNCR unit :**
  **5,000 - 20,000 €/a (depending on the N content in the fuel)**

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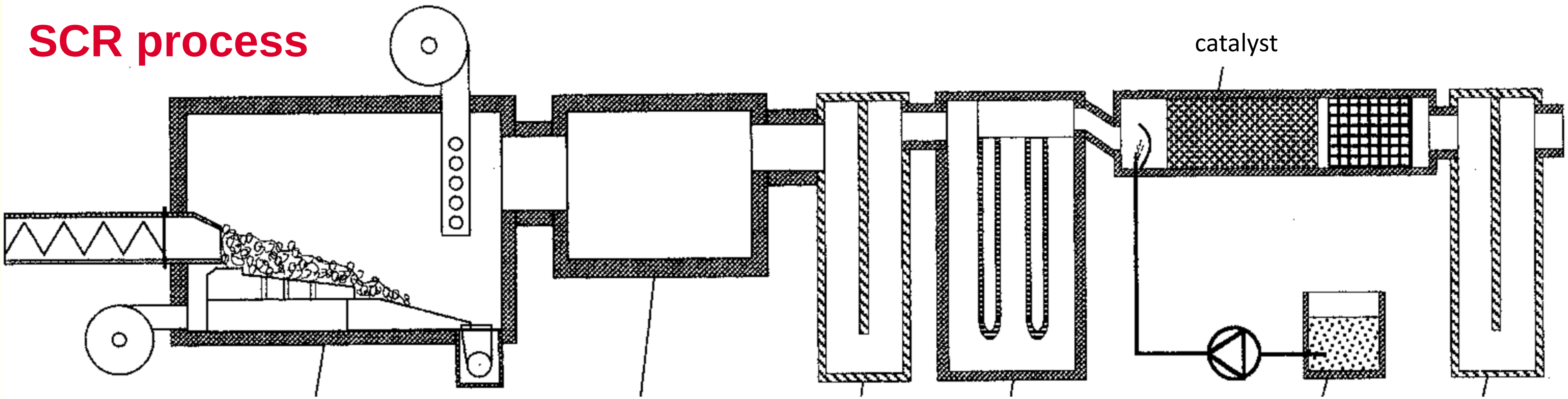
# $NO_x$-reduction by secondary measures

## SCR process




**Constraints:**

- reducing agent: ammonia or urea
- stoichiometric coefficient ≈ 1.0
- operation temperature: 220-270°C (ammonia) respectively 400-450°C (urea)
- average $NO_x$-reduction: 80 to 95%
- considerably higher investment costs than SNCR
- lower operating costs concerning reducing agent
- catalyst deactivation by alkali metals represents a major problem

# Summary and conclusions

# Conclusions (I) – Investigation of release profiles based on lab-scale reactor tests

**The results of the lab-scale reactor tests provide valuable information about different aspects of fixed-bed combustion**

- **Thermal decomposition behaviour as well as data concerning the main flue gas species released from the fuel during devolatilisation and charcoal combustion**
  **➔ data can further be used for the development, validation and calibration of models for fixed-bed combustion**

- **Comprehensive data on the release of $NO_x$ precursors**
  **➔ can be applied as input data for $NO_x$ post-processing in CFD simulations**

- **Data regarding ash related problems**
  **➔ indications regarding the ash melting behaviour**
  **➔ estimation of aerosol and deposit formation tendencies**
  **➔ release data can be used for subsequent CFD-based aerosol and deposit formation modelling**

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# Conclusions (II) – Investigation of release profiles based on lab-scale reactor tests

## N-species release from the fuel bed

- Major $NO_x$ precursors released are HCN and $NH_3$
  - Clearly $NH_3$-dominated: waste wood pellets, straw pellets, Miscanthus pellets, sewage sludge
  - HCN-dominated: softwood pellets, spruce woodchips, beech woodchips
  - Similar $NH_3$ and HCN release was observed for: torrefied softwood, SRC poplar
  - Wood fuels except torrefied softwood show higher NO fraction
- NO and $NO_2$ are also released but to a smaller extent than $NH_3$ and HCN
- N-species release is relevant for $NO_x$ formation modelling

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# Conclusions (III) – CFD simulations of $NO_x$ emissions

- **3D simulations of biomass grate furnaces with a CFD $NO_x$ post-processor including detailed chemistry are a valuable tool to predict $NO_x$ emissions.**
- **Detailed information of $NO_x$ formation and reduction in grate combustion plants as well as relevant influencing parameters can be gained.**
- **Good qualitative and semi-qualitative agreement of simulation results with measurements achieved for different biomass fuels.**
- **The $NO_x$ postprocessor for biomass grate furnaces is a powerful tool for the design and optimisation of furnace geometries and process control in order to optimize $NO_x$ reduction by primary measures but also to design SNCR system integration**

# Conclusions (IV) – $NO_x$ reduction by primary measures

- The air ratio in the primary combustion chamber is the most important influencing parameter regarding $NO_x$ emissions
- The lowest $NO_x$ emissions were detected at an air ratio in the primary combustion chamber of 0.9 – 1.0
- False air input should be minimised because it cannot be controlled
- The results also show that the residence time (volume of the PCC) has a relevant influence on $NO_x$ emissions (this influence seems to get of rising importance the smaller the residence time available in the PCC is). A residence time of at least 0.5 s can be recommended for low-$NO_x$ operation.
- The temperature in the PCC has a minor influence on $NO_x$ emissions as long as it is in the target range of 900 – 1,100°C.
- Flue gas recirculation above the grate seems to be slightly more efficient regarding $NO_x$ reduction than flue gas recirculation below the grate (at same temperature conditions)

→ The potential to reduce $NO_x$ emissions by primary measures is considerable (typically in the range of 30 – 50%)

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# Conclusions (V) – $NO_x$ reduction by secondary measures

- **SNCR process:**
  - **Average $NO_x$-reduction: 60 to 70%**
  - **Moderate investment costs but higher operating costs**
- **SNCR process:**
  - **Average $NO_x$-reduction: 80 to 95%**
  - **Higher investment costs but lower operating cost**

→ **Secondary measures should always be combined with primary measures**

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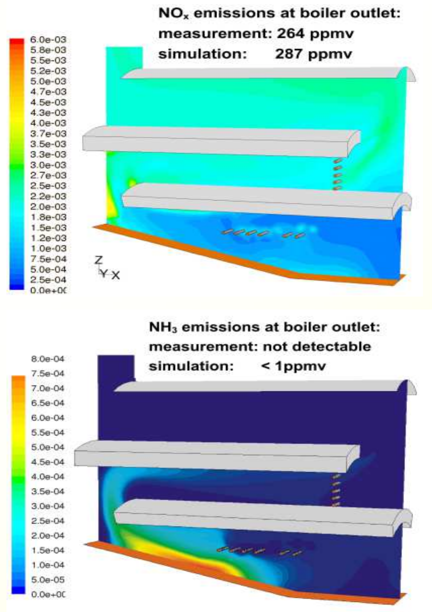
# Thank you for your attention

## DI Dr. Ingwald Obernberger

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