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COMBUSTION SCALING OF FBC

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METHODOLOGIES OF SCALING

Scaling is carried out by

- Formulation and solution of the fundamental equations describing the processes together with their boundary conditions
- Using these equations and boundaty conditions to formulate dimensionless criteria Z_1, Z_2 …

Two processesses I and II are similar when the dimensionless criteria are equal

$$Z_{1,I} = Z_{1,II}$$

$$Z_{2,I} = Z_{2,II}$$

ON THE SCALING OF FB BOILERS

Scaling from one size to another can be done in many ways and for many purposes:

- Fluid dynamic scaling (from cold to hot conditions)
- Combustion scaling (from lab reactor to boiler)
- Boiler scaling (scale-up of boilers)

FLUID DYNAMIC SCALING

Based on the dimensionless form of the fluid dynamic equations, including contituitive relationships:

$$\frac{u_0^2}{gL}, \frac{\rho_s}{\rho_f}, \frac{\rho_s u_0 d_p^2}{\mu L}, \frac{\rho_f u_0 L}{\mu}, \frac{G_s}{\rho_s u_0}, geometry, \varphi, PSD$$

5 Numbers

Simplifications

$$\frac{u_0^2}{gL}, \frac{\rho_s}{\rho_f}, \frac{u_0}{u_{mf}}, \frac{G_s}{\rho_s u_0}, geometry, \varphi, PSD$$

4 Numbers

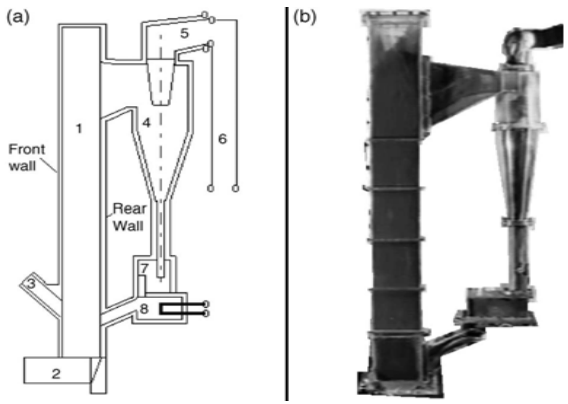
Further simplifications

$$\frac{u_0^2}{gL}, \frac{u_0}{u_{mf}}, \frac{G_s}{\rho_s u_0}, geometry, \varphi, PSD$$

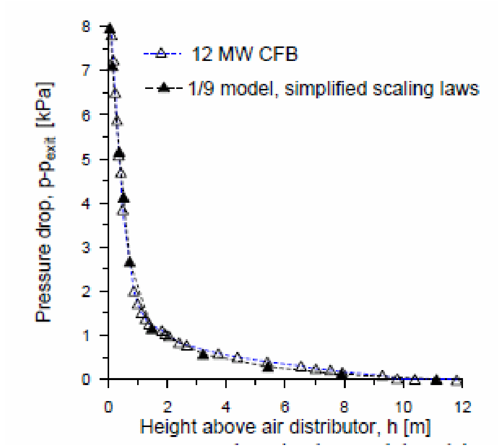
3 Numbers

FLUID DYNAMIC SCALING—EXAMPLE: 1/9th cold model

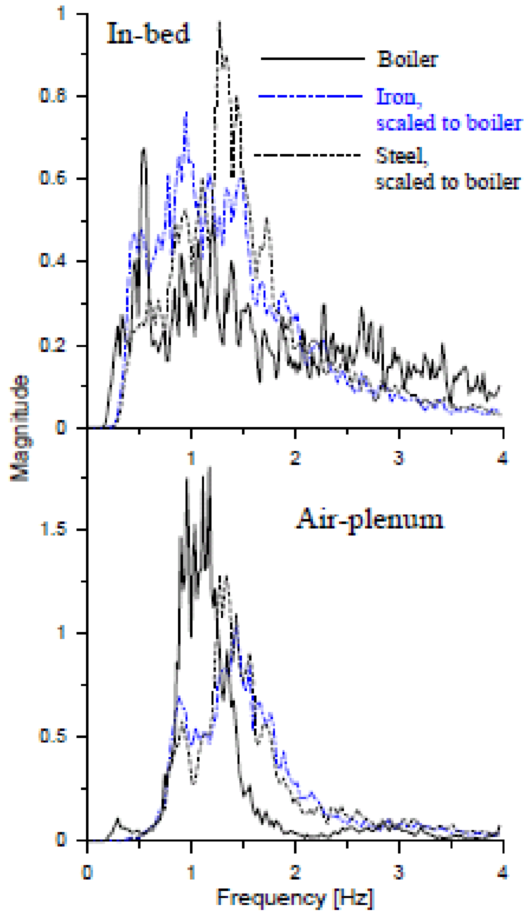
The beds



Pressure drops



Pressure fluctuations



The particles

Sand Iron Steel

COMBUSTION SCALING I: Simplifications

In combustion scaling most operation parameters are similar in Plant I and Plant II

- $T_I = T_{II}$ Temperature
- $\lambda_I = \lambda_{II}$ Total excess-air ratio
- $\varphi_I = \varphi_{II}$ Primary-zone stoichiometry
- Same fuel
- Same bed material
- $u_I \approx u_{II}$ Almost same fluidisation velocities

COMBUSTION SCALING: FLUID DYNAMICS

With the similar operation criteria in Plant I and II, most of the fluid dynamic criteria are similar. Only the geometry (height L or width D) and $G_s/(\rho u_o)$ remain.

The latter criterion is similar to the concentration c_s at the top of the furnace (L):

$$\frac{G_s}{\rho_s u_0} = \frac{\rho_s(1-\varepsilon)(u_0 - u_t)}{\rho_s u_0} \approx 1 - \varepsilon = c_s(L)$$

On an average

$$\overline{c}_s = \frac{\Delta P}{g\rho_s L}$$ which gives $$\Delta P_I = L_I \Delta P_{II} / L_{II}$$

COMBUSTION SCALING: COMBUSTION

Drying, devolatilisaton and char combustion are to be compared with mixing of the fuel in the furnace. The dimensionless species transport equation

$$\mathrm{div}\left(\bar{\mathbf{U}}C_i\right) = \frac{1}{\mathrm{Pe_i}}\mathrm{div}\left(\mathrm{grad}\ C_i\right) + \mathrm{Da_{i,v}}$$

$$\mathrm{Pe_i}\ \mathrm{div}\left(\bar{\mathbf{U}}C_i\right) = \mathrm{div}\left(\mathrm{grad}\ C_i\right) + \mathrm{Da_{i,h}}$$

gives the dimensionless criteria

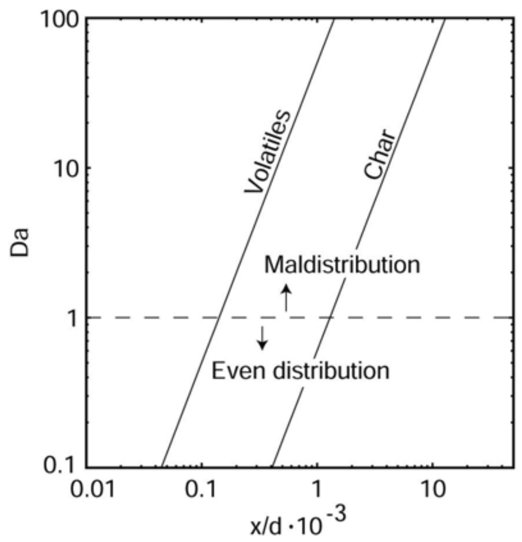
$$Da_{i,v} = R_i x_0 /(c_0 u_0) \qquad\qquad Da_{i,h} = R_i x_0^2 /(D_i c_0)$$

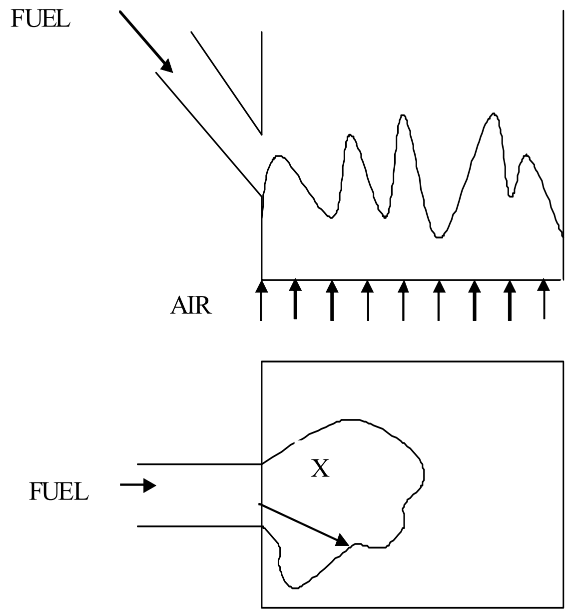
where Da are the first and second Damköhler numbers or in general

Da=transport time/reaction time

COMBUSTION SCALING: HORIZONTAL

- Transport (mixing) time $\tau_{disp} = x^2/(2D_h)$
- Devolatilisation time $\tau_{dev} = a_1 d_p^{a_2}$
- Char combustion time $\tau_{char} = \dfrac{\rho_c d_p^2}{4M_c ShDc_{ox}}$





COMBUSTION SCALING: VERTICAL

$$Da_{i,v} = R_i x_0 /(c_0 u_0) => L_I / u_{o,I} = L_{II} / u_{o,II}$$

since R and c are already equal and x_o=L.

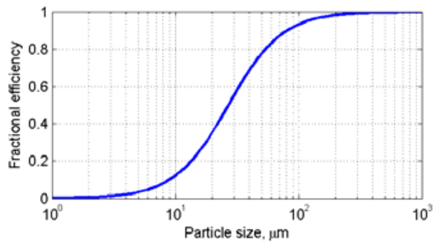
L/u is gas residence time (transport time).

Particle residence time is nL/u_p, where n is the circulation number and the particle velocity $u_p=u_o-u_t$.

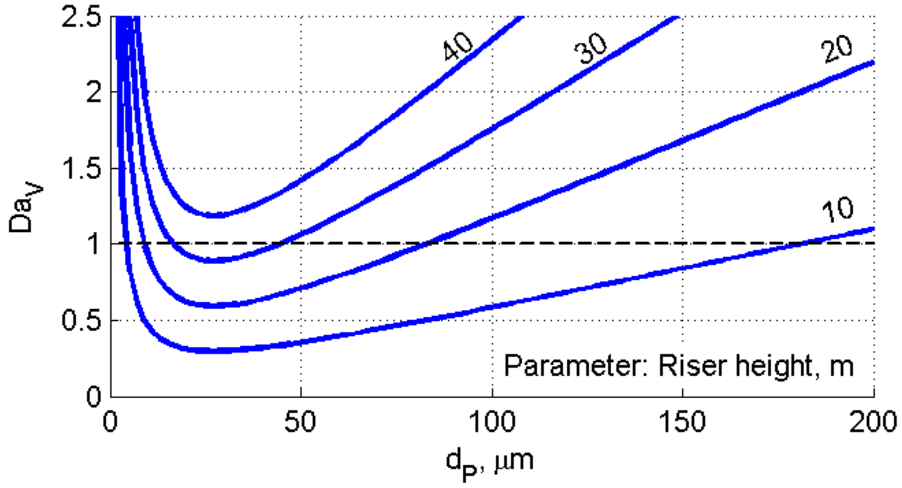
$$n = 1/(1-\eta)$$

and the cyclon efficiency

$$\eta = \frac{1}{1+\left(d_{p,50} / d_{\mathrm{P}}\right)^m}$$



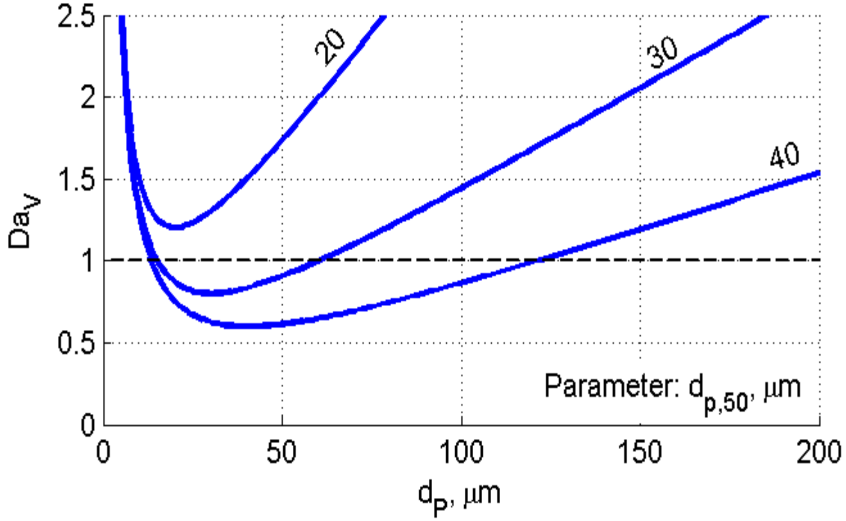
INFLUENCE OF RESIDENCE TIME



d_{p50} =27 μm

Temperature 850 °C

Oxygen concentration 5%



L=30 m

CYCLONE SCALING

The cyclone is influenced by a great number of parameters

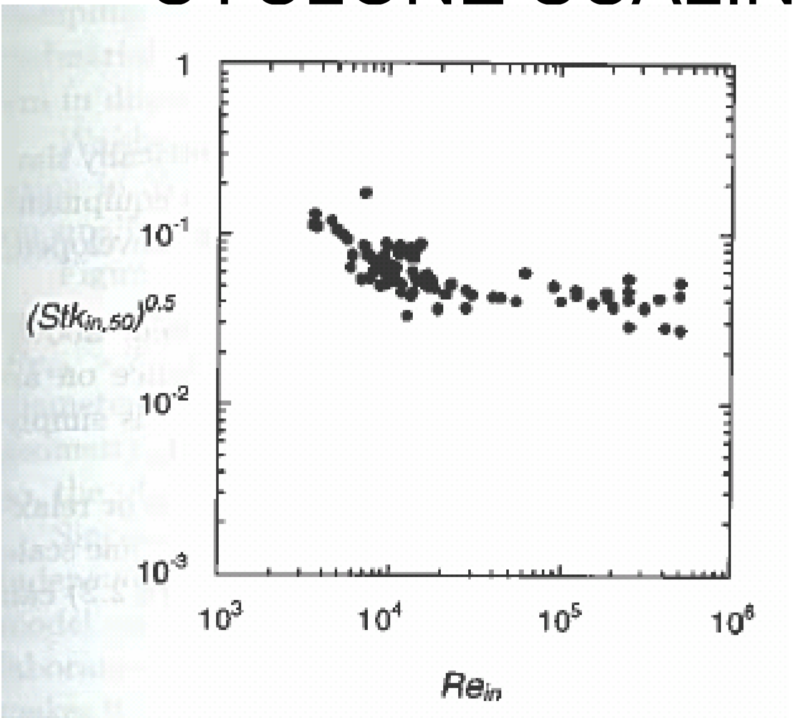
- particle properties
- solids as a whole (e.g. concentration)
- gas properties
- cyclone configuration
- force field

But with some simplification (low-loaded cyclones) for similar geometries the efficiency can be expressed as

$$\eta(d_p) = f(\mathrm{Re}, Stk)$$

$$Stk = \frac{d_{p50}^2 u_{in} \Delta\rho}{18\mu D}$$

CYCLONE SCALING



Above a certain Re the efficiency scaling is even more simplified

$$\eta(d_p) = f(Stk)$$

CYCLONE SCALING: HIGH-LOADED CYCLONES

According to one of Muschelknautz' formulations, the cyclone efficiency of a cyclone with inlet loading c_o is

$$\eta = (1 - \frac{c_{o,L}(d_{p,50})}{c_o}) + \frac{c_{o,L}(d_{p,50})}{c_o} \sum_{i=1}^{N} \eta_i m_i$$

where $c_{o,L}$ is a limiting loading, separating out the ”saltation” part from the ”inner vortex” part. Both parts depend on Stokes number, and for scaling

$$\eta(d_p) = f(Stk, c_{o,L} / c_o)$$

THE IMPACT OF THE CYCLON

At the same combustion conditions the fuel powers of combustors I an II are

$$P_I \propto uA_{r,I} \propto u_{cycl} D_I^2$$

$$P_{II} \propto uA_{r,II} \propto u_{cycl} D_{II}^2$$

$$\frac{P_I}{P_{II}} = \frac{D_I^2}{D_{II}^2}$$

Stokes number scaling

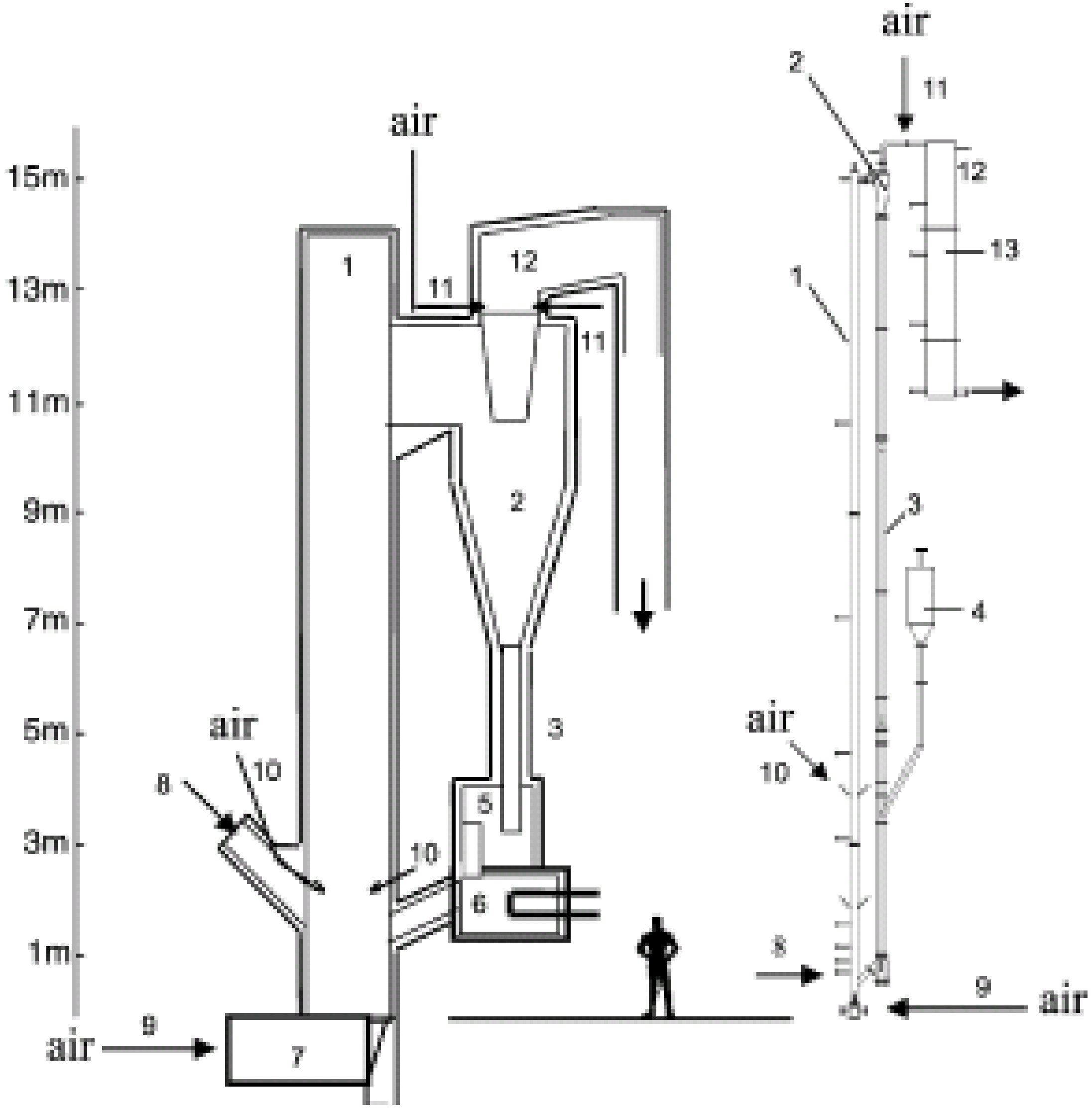
$$\frac{d_{p50,I}^{\,2} u_{in} \Delta\rho}{9\mu D_I} = \frac{d_{p50,II}^{\,2} u_{in} \Delta\rho}{9\mu D_{II}}$$

$$\frac{d_{p50,I}^{\,2}}{d_{p50,II}^{\,2}} = \frac{D_I}{D_{II}}$$

The cyclon efficiency is strongly proportional to the size of equipment

$$\left(\frac{d_{p50,I}}{d_{p50,II}}\right)^4 = \frac{P_I}{P_{II}}$$

COMPARISON BETWEEN TWO PLANTS USED FOR COMBUSTION SCALING

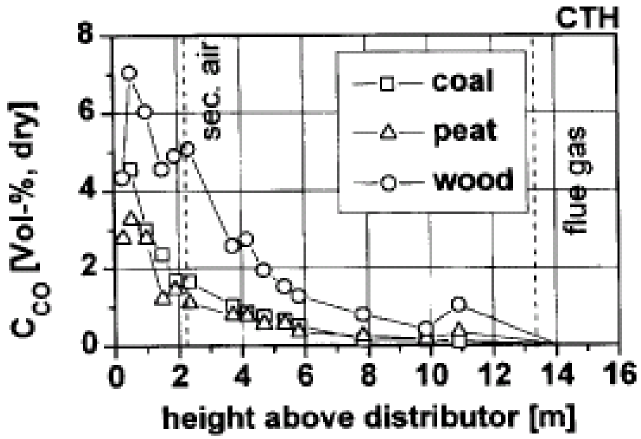


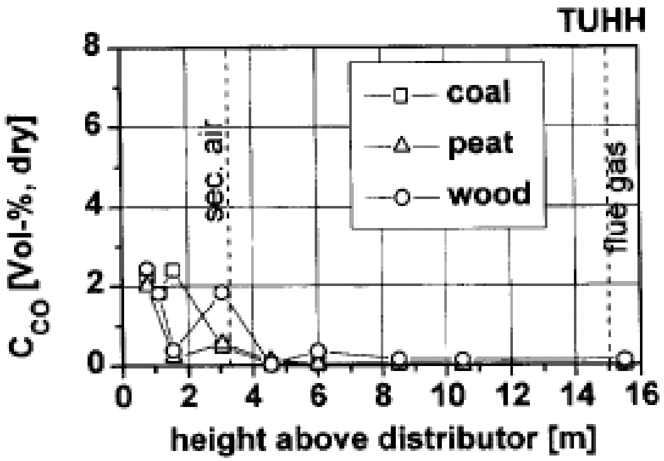
Gas residence times in CFB units of different scales

	TUHH	CTH	Flensburg
Volume of combustion chamber, m^3	0.13	31.4	590
Volume of cyclone including the entry duct, m^3	0.024	12.4	490
Volume of after-burner chamber, m^3	0.13	10.7	–
Gas residence time in combustion chamber, τ_{cc}, s	2.6	2.2	3.8
Gas residence time in cyclone, τ_c, s	0.5	0.9	3.2
Gas residence time in after-burner chamber, τ_{ac}, s	2.7	0.8	–
Gas residence time in burn-out zone, $\tau_c + \tau_{ac}$, s	3.2	1.6	3.2
Ratio of gas residence times			
τ_c/τ_{cc}	0.2	0.4	0.8
$\tau_c + \tau_{ac}/\tau_{cc}$	1.2	0.7	0.8

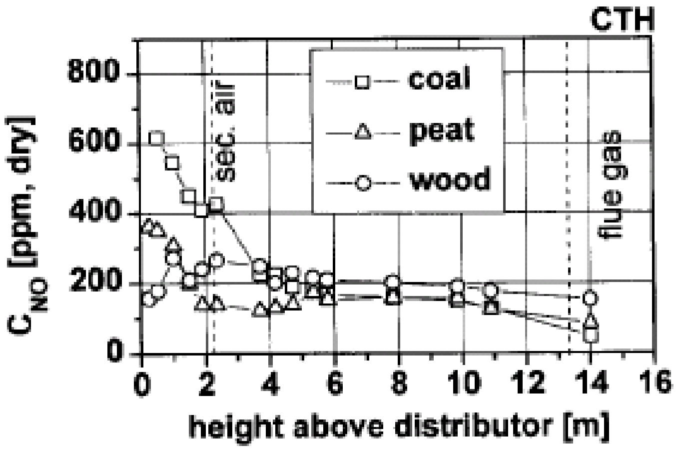
EXAMPLE: (Knöbig et al.) COMPARISON OF EMISSIONS FROM LAB RIG AND BOILER

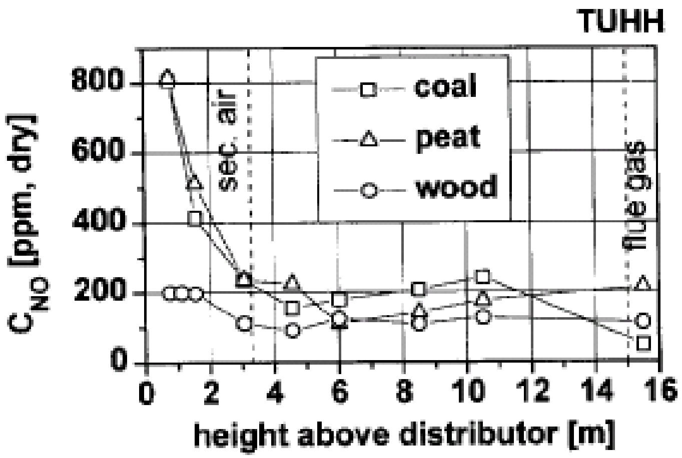
CARBON MONOXIDE





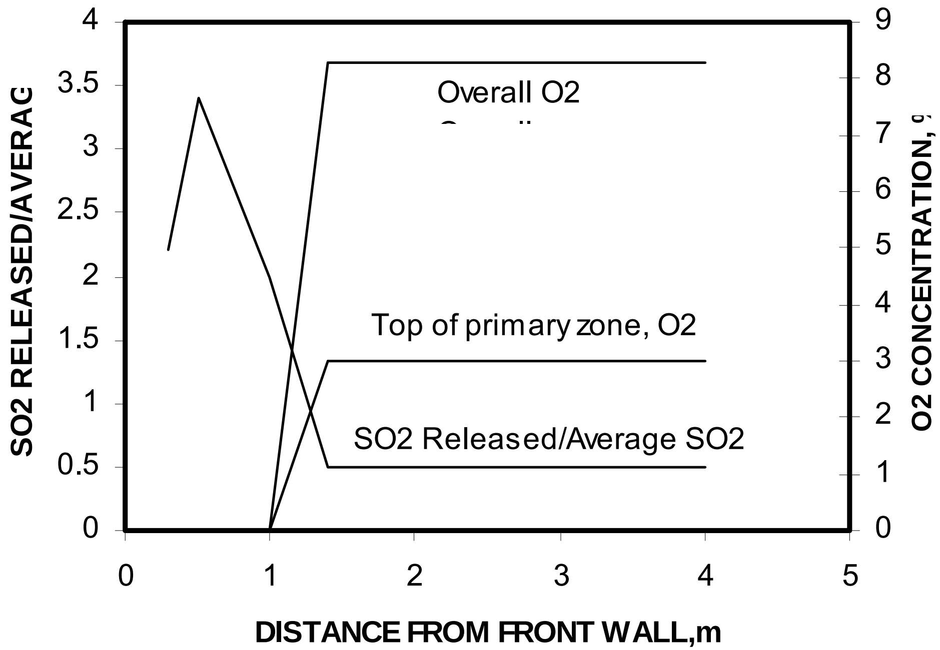
NITRIC OXIDE





EXAMPLE (Alliston and Wu): DESULPHURIZATION

In comparisons between desulphurisation with the same coal and limestone in a test rig and boilers, the test rig always showed the best performance!



CLASSICAL BED SCALING

In the Z=z/L direction the species transport equation is

$$U\frac{dC}{dZ} = Da_v$$ and in dimensional form $$u\frac{dc}{dz} = R$$

For the two-phase bed this can be written

$$\varepsilon_b(u_0 - u_{mf})\frac{dc_b}{dz} = \varepsilon_b R_{gg} - \varepsilon_b a_b k_{be}(c_b - c_e)$$

$$\varepsilon_e u_{mf}\frac{dc_e}{dz} = (1-\varepsilon_e)(1-\varepsilon_b)\sigma_c R_{gs} + \varepsilon_b a_b k_{be}(c_b - c_e)$$

or in dimensionless form

$$\varepsilon_b\beta\frac{dC_b}{dZ} = \varepsilon_b Da_{gg} - NTU(C_b - C_e)$$

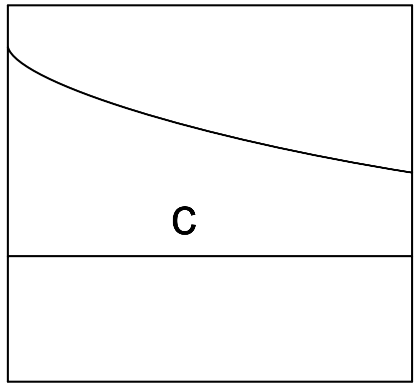
$$\varepsilon_e(1-\beta)\frac{dC_e}{dZ} = (1-\varepsilon_e)(1-\varepsilon_b)\sigma_c Da_{gs} + NTU(C_b - C_e)$$

CLASSICAL BED: DIMENSIONLESS CRITERIA

- Gas-gas Damköhler number $Da_{gg} = K_{gg} C_b L / u_o;$
- Gas-solid Damköhler number $Da_{gs} = K_{gs} C_e L / u_o;$
- Bed Number of Transfer Units $NTU = \varepsilon_b a_b k_{be} L / u_0;$
- Gas-flow partition number $\beta = u_0 - u_{mf} / u_0;$

A most simplified result

$$C_{z=L} = exp(-\frac{Da_{gs} NTU}{Da_{gs} + NTU})$$



CFB BOILER SCALE-UP

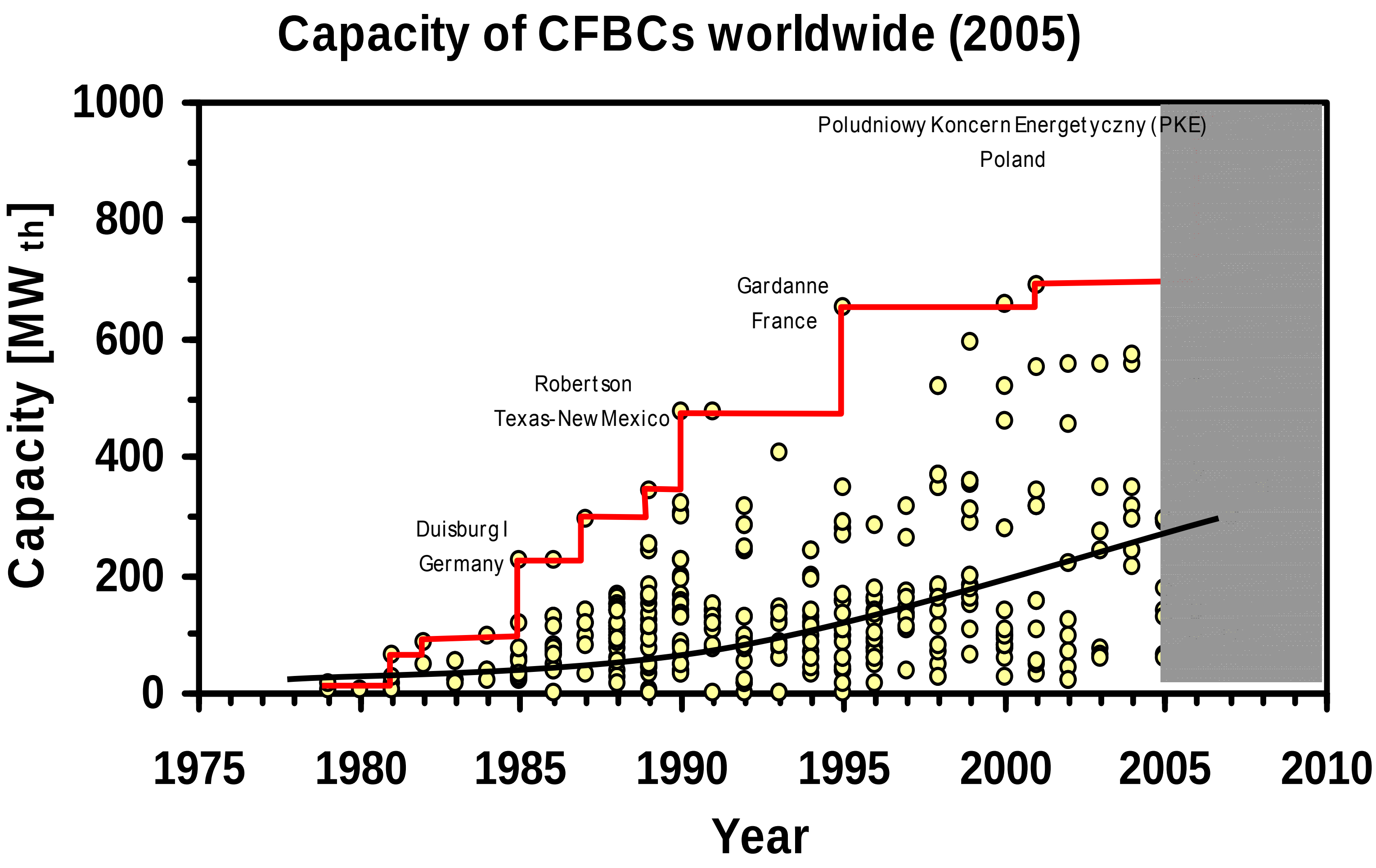
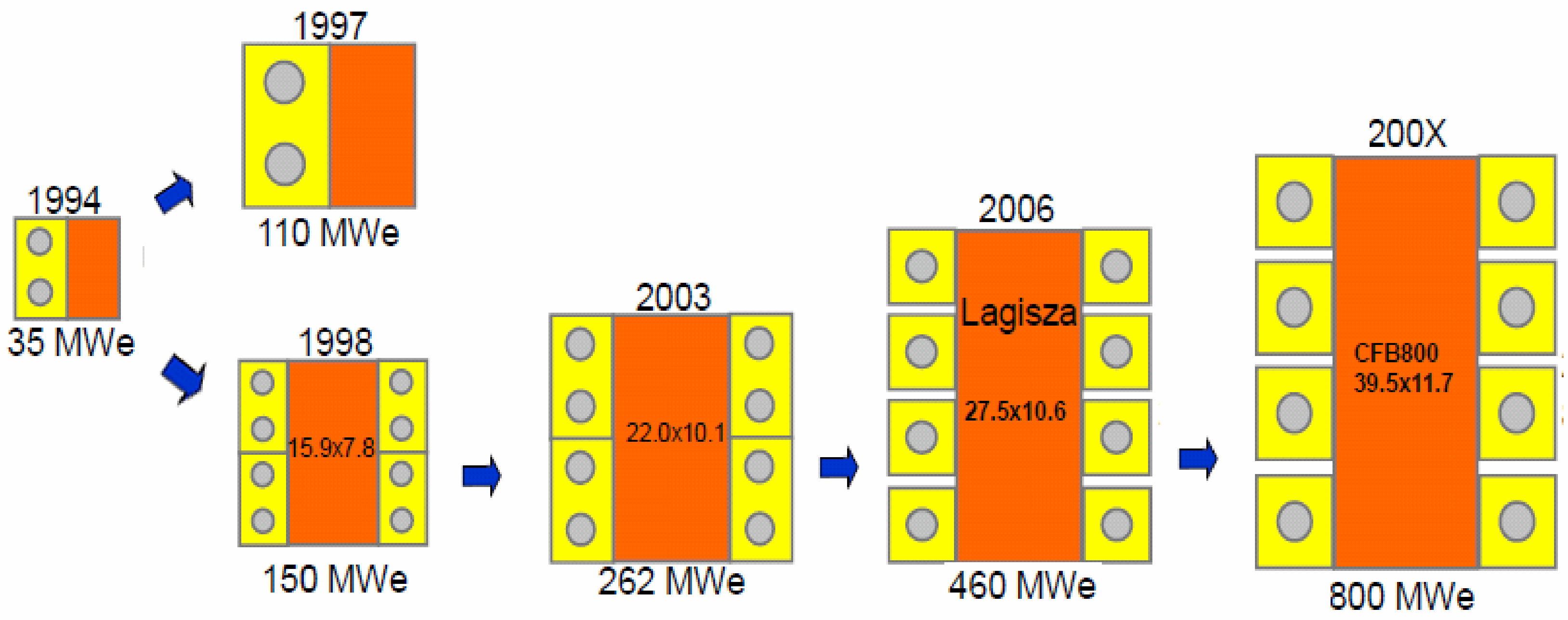
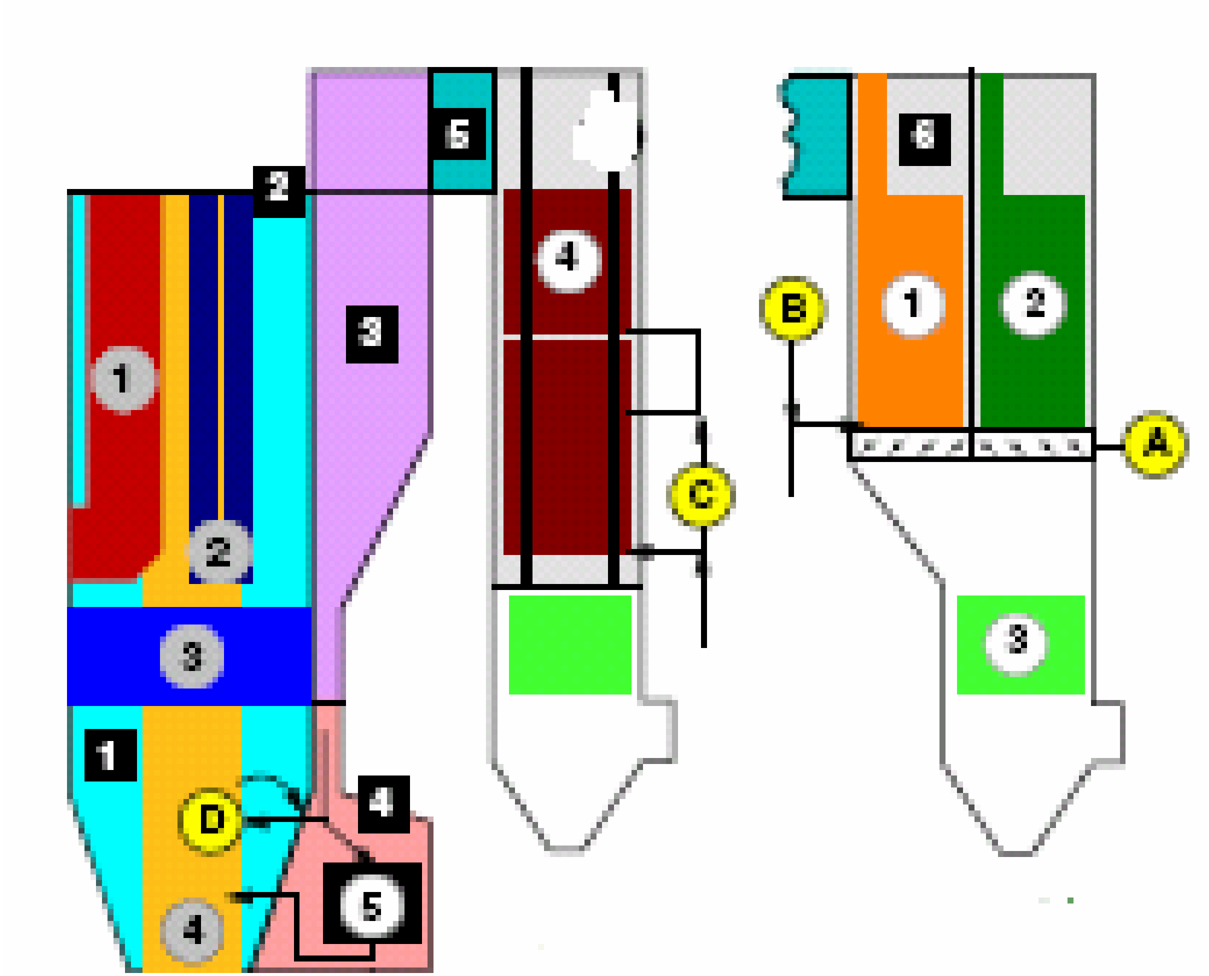


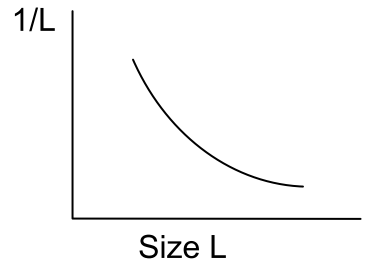
Diagram from M. Hupa 2005

MODULAR SCALE-UP (Foster Wheeler)

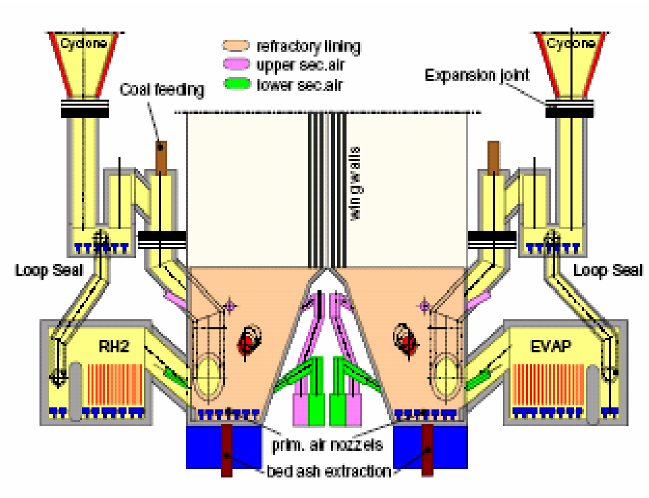


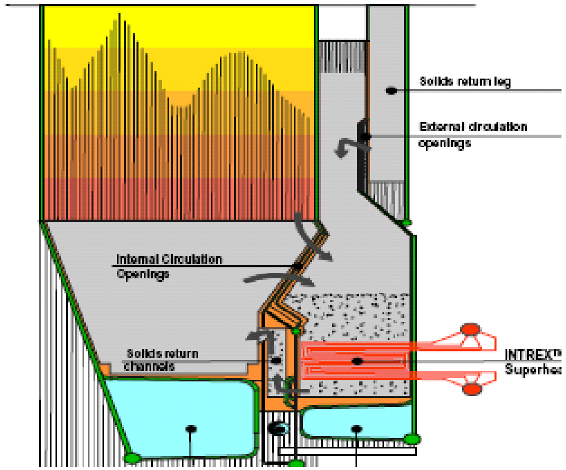
ALLOCATION OF HEAT TRANSFER SURFACE

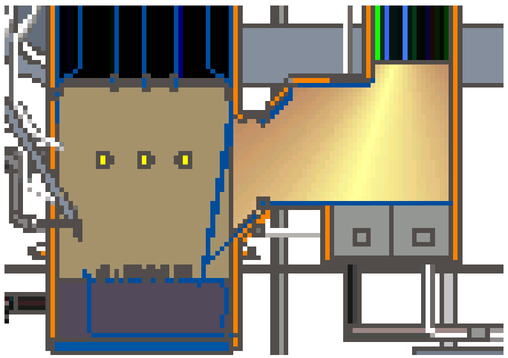




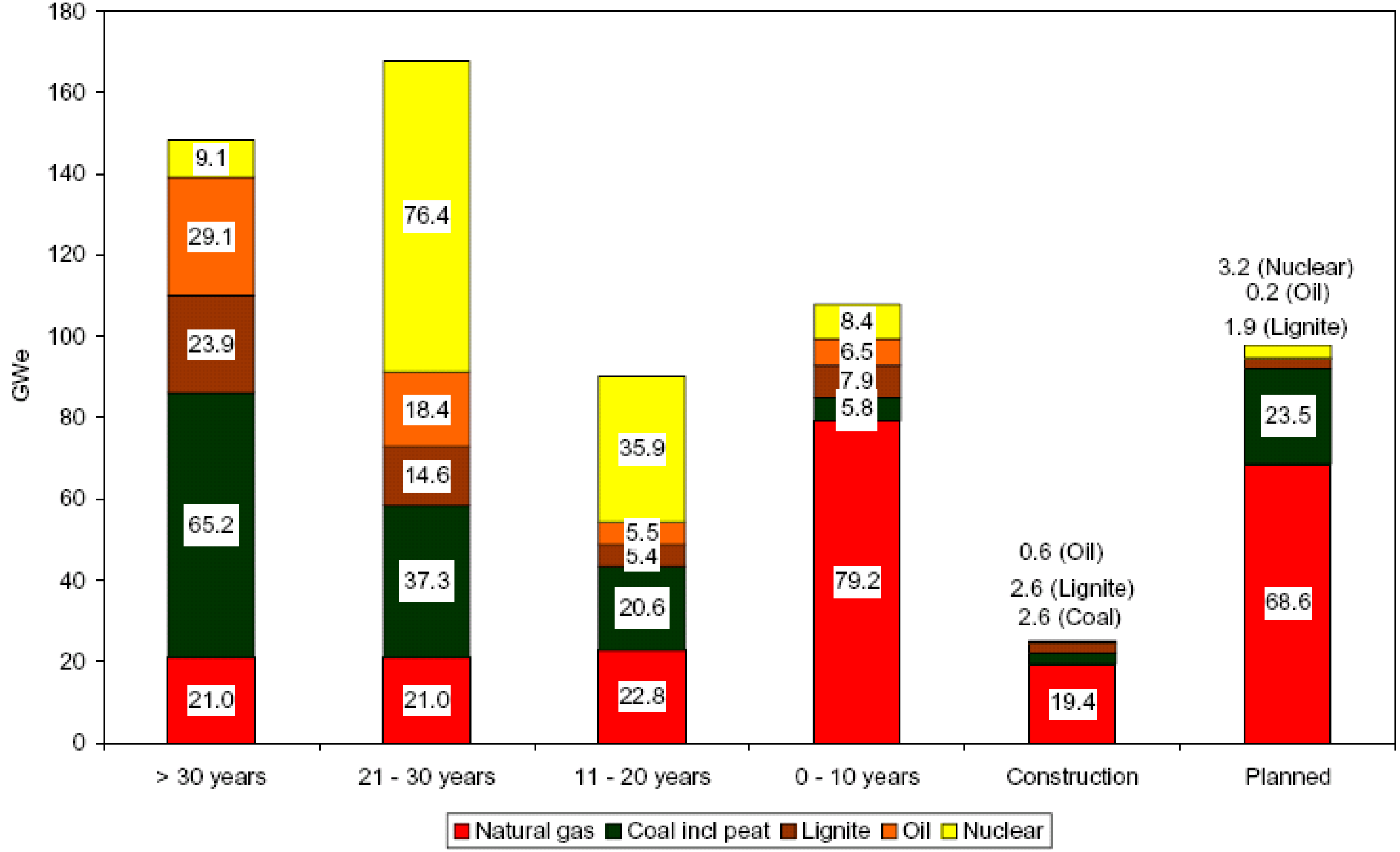
BOTTOM REGIONS FROM VARIOUS MANUFACTURERS







Net capacity of thermal power plants in EU-25 by fuel and age 2006



Comparison between conceptual designs

Item	**Foster Wheeler [25]**	**Alstom [26]**
Size MW_e	800	450-600
Steam pressure bar	315 (design pressure)	270 (header outlet)
Steam temperature,^{o}C	604/621	600/620
Separators	8	6
Bed cooling except walls	Internal walls+INTREX (10-20 MW_{th} each), 8 consisting of two in series	External heat exchangers (No size limitation)
Size	10 m wide to allow penetration of secondary air, pant-leg in Alstom. Less than 50 m high, and as wide as needed for the power of 2.5-4 MW_{th}/m^2 cross-section area	

CONCLUSIONS

- Strict scaling is impossible.
- Fluid dynamical scaling is useful to represent the flow patterns of hot large-scale boilers in cold small-scale test-rigs.
- Combustion scaling is possible if reactors with similar operation data are compared. Often, the horzontal dimension cannot be scaled, but the vertical can.
- The influence of cyclone operation on test results has not been stated in literature
- Boiler scaling utilises building-stones from smaller scales that are duplicated to obtain larger scales.

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