



*Oxy-fuel combustion in GHG Context – Status of
Research, Technology and Assessment*

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CRC for Coal in Sustainable Development

Uni of Newcastle Australia

for

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OVERVIEW



- Introduction
- Laboratory investigations
- Pilot scale studies
- Economic assessments
- Australian scene
- Summary & technical challenges

Technologies for capture of CO₂

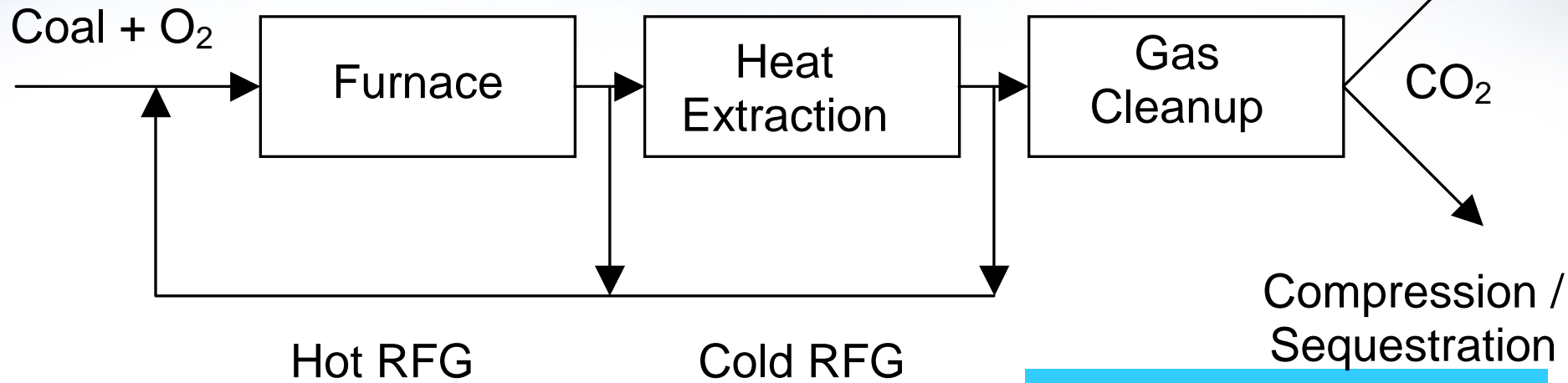


A concentrated stream of CO₂ is needed for sequestration. Three ways to produce sequestration ready stream:

- Post-combustion capture - CO₂ capture using MEA type solvents
- IGCC - Carbon is removal before combustion
- Oxy-Fuel – using oxygen for the combustion

General flow sheet for oxy-fuel with (RFG)

Driver 2, reduced gas clean up costs, compared to air firing



Driver 3, reduced NO_x emissions, compared to air firing

Driver 1, sequestration ready CO_2

Issues in Oxy-Firing



- Combustion Issues
 - Kinetics
- Ash related issues
 - Ash formation and deposits
- Pollutant issues
 - SO_x, NO_x, Hg, Fine particles
- Heat transfer issues
 - Flame emissivity
- Technology issues
 - ASU, Economic feasibility, Retrofit

Laboratory Scale Tests



The following investigations were done in different laboratory studies:

- Effect of lower diffusivity on flame speed was demonstrated in micro-gravity tests
- The mechanisms of reduced NO_x in oxy-RFG were investigated by Char oxidation has been investigated in oxygen enriched environment.
- Desulphurisation was found to improve in oxy-RFG case
- Char reactivity has been investigated in different environments – Particle temp was found to be slightly lower in CO₂ environment
- Trace elements behaviour was investigated by thermodynamic equilibrium calcs.



Pilot Scale Studies

- Argonne National Laboratory
- IFRF
- IHI/CCUJ
- CANMET
- Air Liquide

Argonne National Lab/EERC - 1988

The earliest study of coal oxy-fuel combustion in a pilot-scale furnace was carried out by EERC for ANL in their 3 MWt pilot facility to test performance

Summary

- Recycle ratios estimated: For a wet recycle ratio of 0.76 and for a dry recycle 0.73 matched the overall heat transfer performance
- Oxy-fuel combustion had a similar in-furnace gas temperature profile as the normal air-fired combustion.
- It was found that oxy-fuel combustion had lower NO_x (50%) and SO_x emissions, and a high carbon burnout compared to air firing.

Conclusion “Oxy-Firing may be applied successfully as a retrofit to a wide range of utility boiler and furnace systems”

IFRF Study 1993-95

IFRF.....Recycled flue gas (RFG) demonstration with primary consideration to retrofitting an existing pf boiler. 2.5 MW (2mX2mX6.2m)

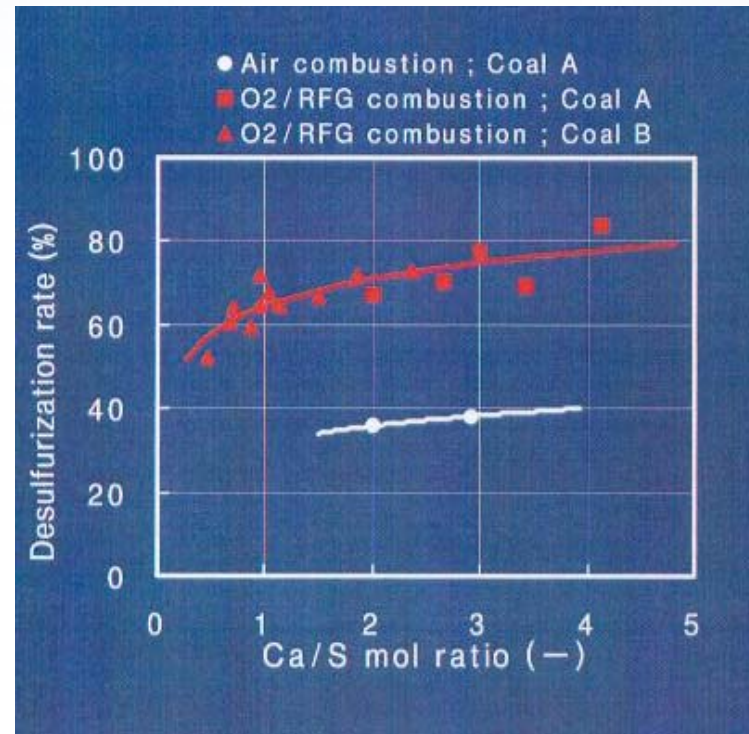
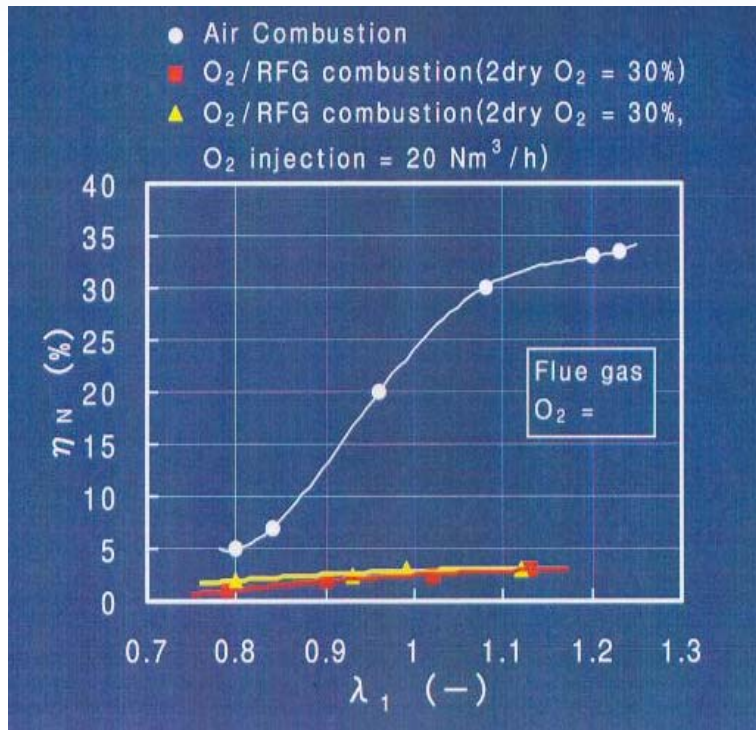
Summary

- Similar to those from ANL/EERC tests
 - Lower NO_x, SO_x, Technical feasibility
- Recycle ratio depended on coal used
- Air leakage resulted in max CO₂ concentration to 91%

IHI Study - 1995

IHI.....Recycled flue gas (RFG) demonstration in 1.2 MWt (1.3mX7.5m) test furnace with primary consideration to reduce NO_x and SO_x pf boiler. **SO_x FGD better.**

NO_x



SO_x

Almost 99% CO₂ was recovered from Flue gas

CANMET Study 1999

IFRF.....Recycled flue gas (RFG) demonstration with primary consideration to retrofitting an existing pf boiler. 0.3 MW (0.6mX6.7m)

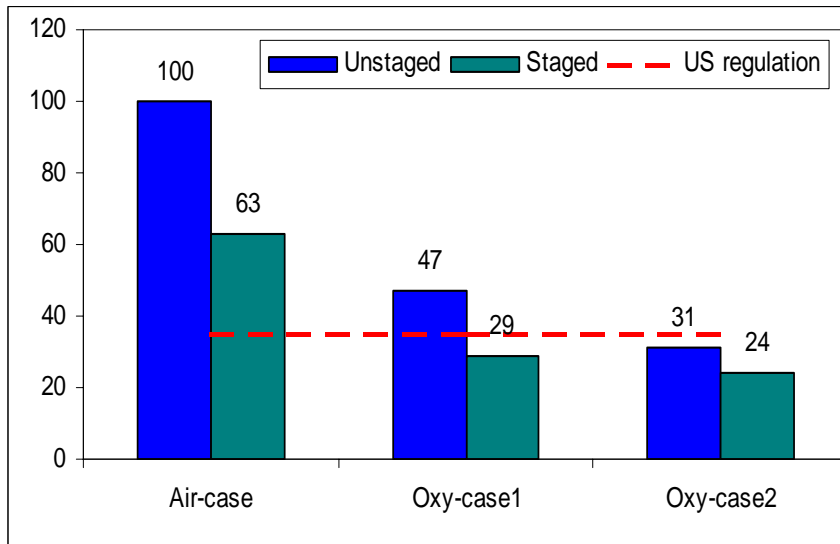
Summary

- Technical feasibility, low NO_x, low SO_x,
- Investigated the effect of oxygen purity recycle and different oxygen concentration in burner
- Decrease in SO_x by higher retention in ash
- Slight increase in N₂ (>3%) increased NO_x emissions
- Wet and dry recycle

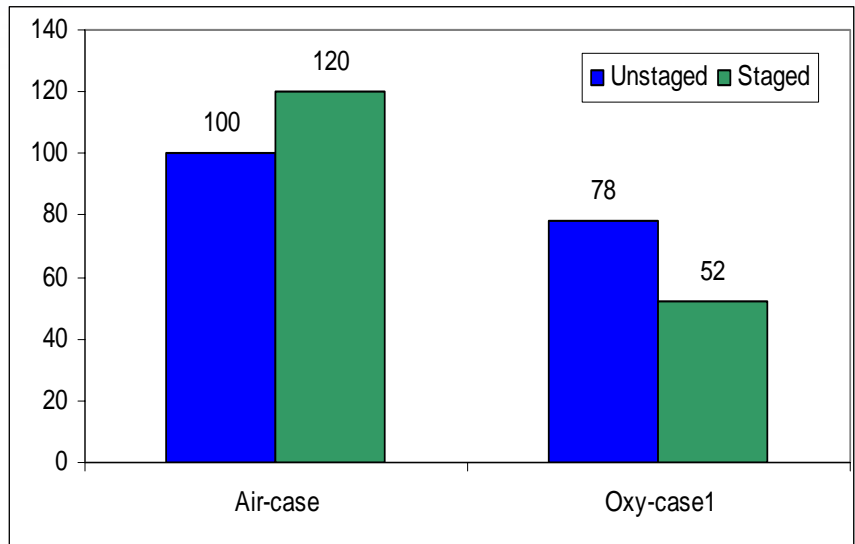
Air Liquide Study - 2002



Objective mainly multi-pollutant control, including staged combustion in 1.5MW_t. For retrofitting existing pf boiler



(a) NO_x emissions, normalised assuming the baseline value in air-case is 100. Dash line is US regulation 65 mg/MJ



(b) Unburnt carbon in ash, normalised assuming the baseline value in air-case is 100.

Conclusions from Pilot Scale Studies



The pilot-scale studies have demonstrated:

- Feasibility of pulverised coal oxy-fuel combustion
- No major technical barriers in pilot-scale studies.
- Oxy-fuel combustion technology suitable for retrofit
- Oxy-fuel combustion achieves clean coal combustion,
 - lowering NO_x,
 - Increasing SO_x removal
 - possibly lower mercury emissions and
 - increased CO₂ concentration for sequestration.



Economic Assessments

- Air Liquide
- CANMET
- IHI/CCUJ
- Vattenfall
- CCSD

Economic Assessments



Technology has been demonstrated only at pilot-scale, not at a practical scale, but demonstrations are planned

- Many assessments of practical systems have been made

Assessment Basis

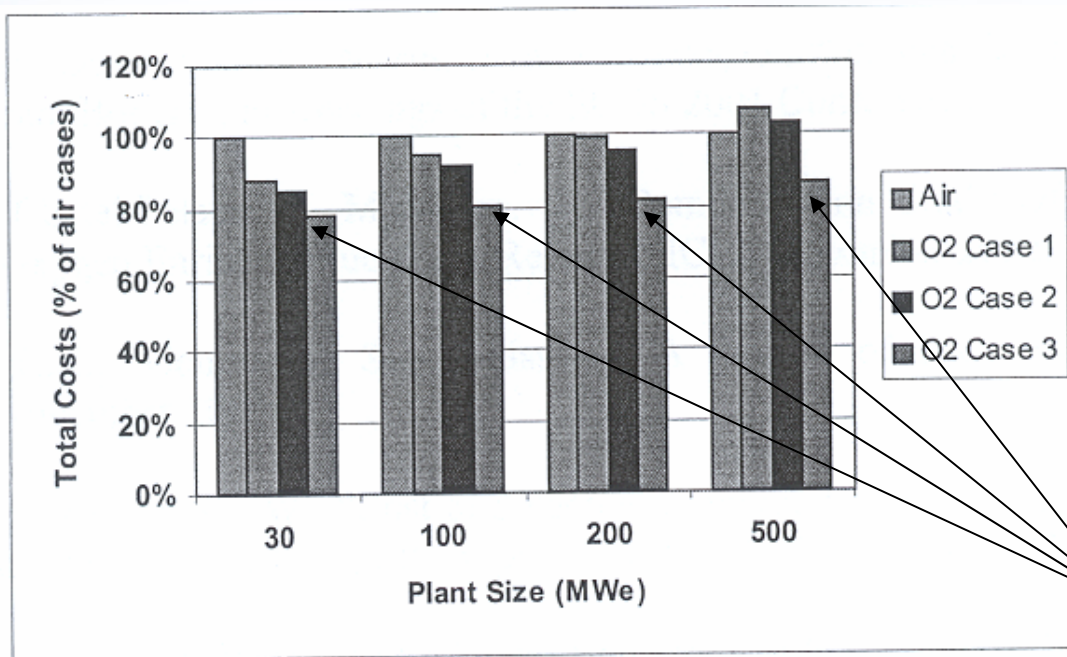
Comparisons have been made comparing oxy-fuel with alternative technologies, based on

- \$ / t CO₂ avoided, COE, compared with pf, PF SC, USC, IGCC, NGCC etc
- Reduction in mass of NO_X emissions compared to pf
- Reduction of capital and operating cost of gas cleanup compared to pf
- In comparing with IGCC, we compare a technology with new process with one not demonstrated at large scale
Uses standard unit operations, there are no substantial technical obstacles.

A1 - Air Liquide/ ICCT



Economics: Capital + operating cost
(operating cost= 0.22 x capital cost)



Three cases:

Case 1: Retrofit: FGD, SCR, ESP, Hg

Case 2: Retrofit: FGD, ESP, Hg

Case 3: New (compact design): FGD, ESP, Hg

Balance between ASU cost with reduced cost of back end gas clean up

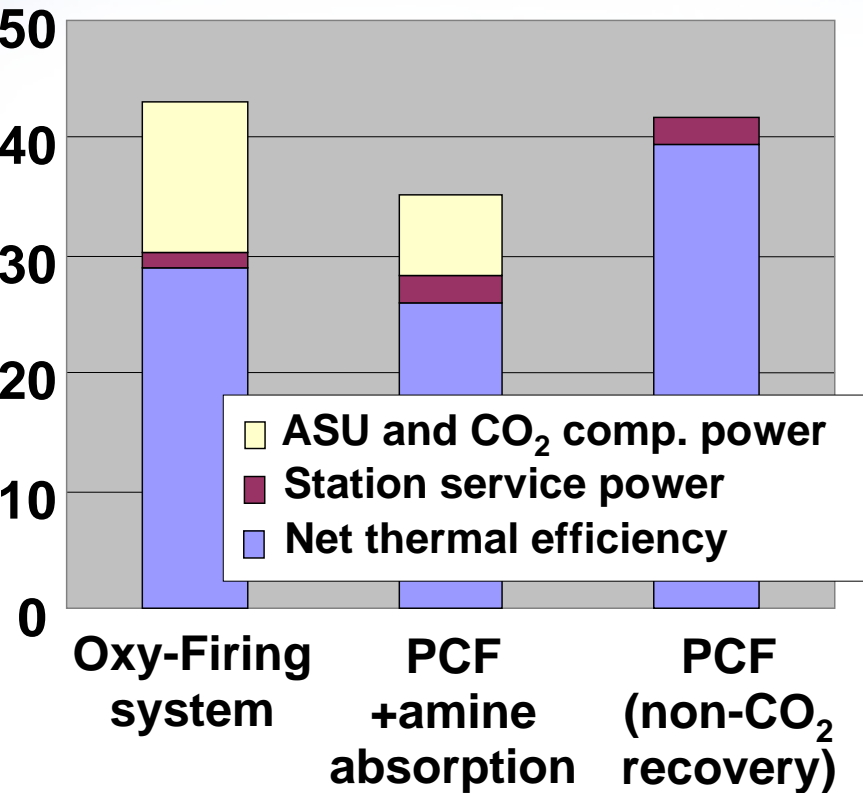
A 2 CANMET – 400 MWe retrofit



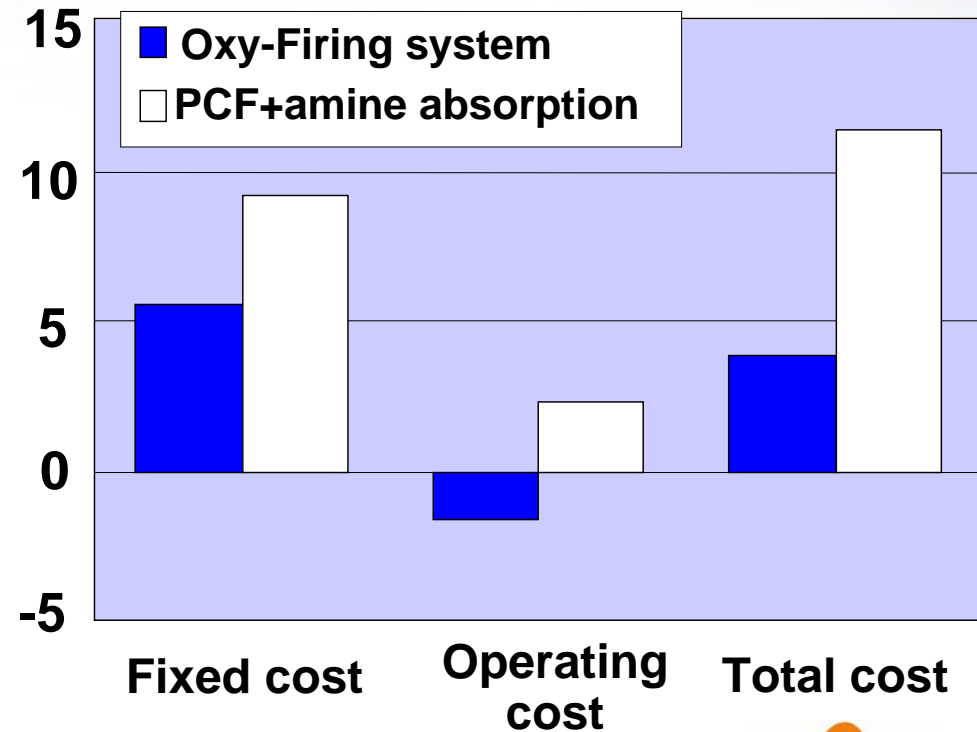
- Considers complete substitution of air by O₂/CO₂, ie no allowance for dual oxidant option
- Supplementary (lost) energy generated from natural gas to maintain original plant output
- Oxyfuel, at US\$25/ton of CO₂ avoided, is ~70% of amine case..... but both are expensive, increasing electricity price by 20-30%.

A3 - IHI /CCUJ A new plant - 1000MWe

Thermal Efficiency (%)



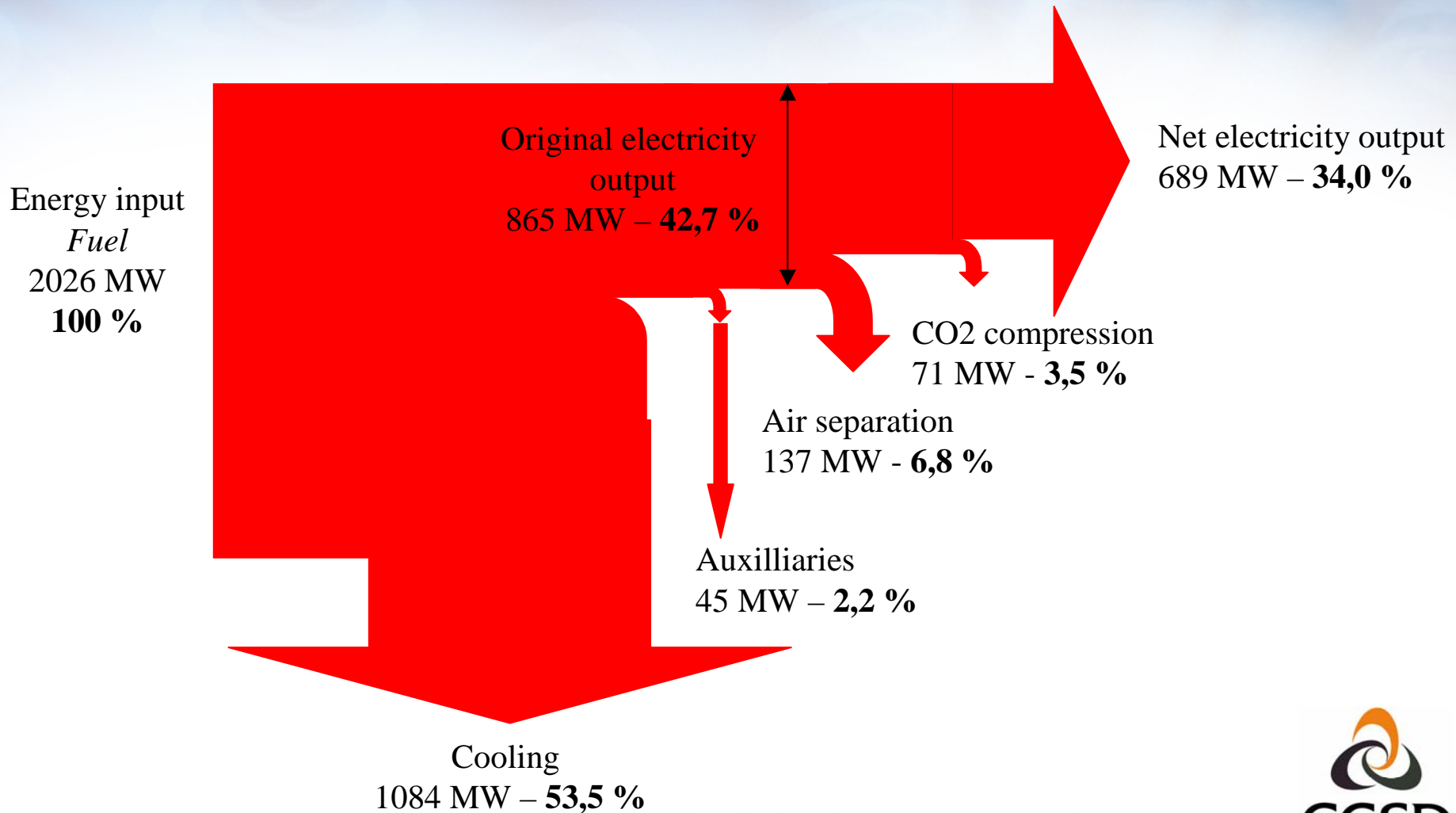
Economy (billion yen/year)



A4 – EU/Vattenfall – Lignite Fired



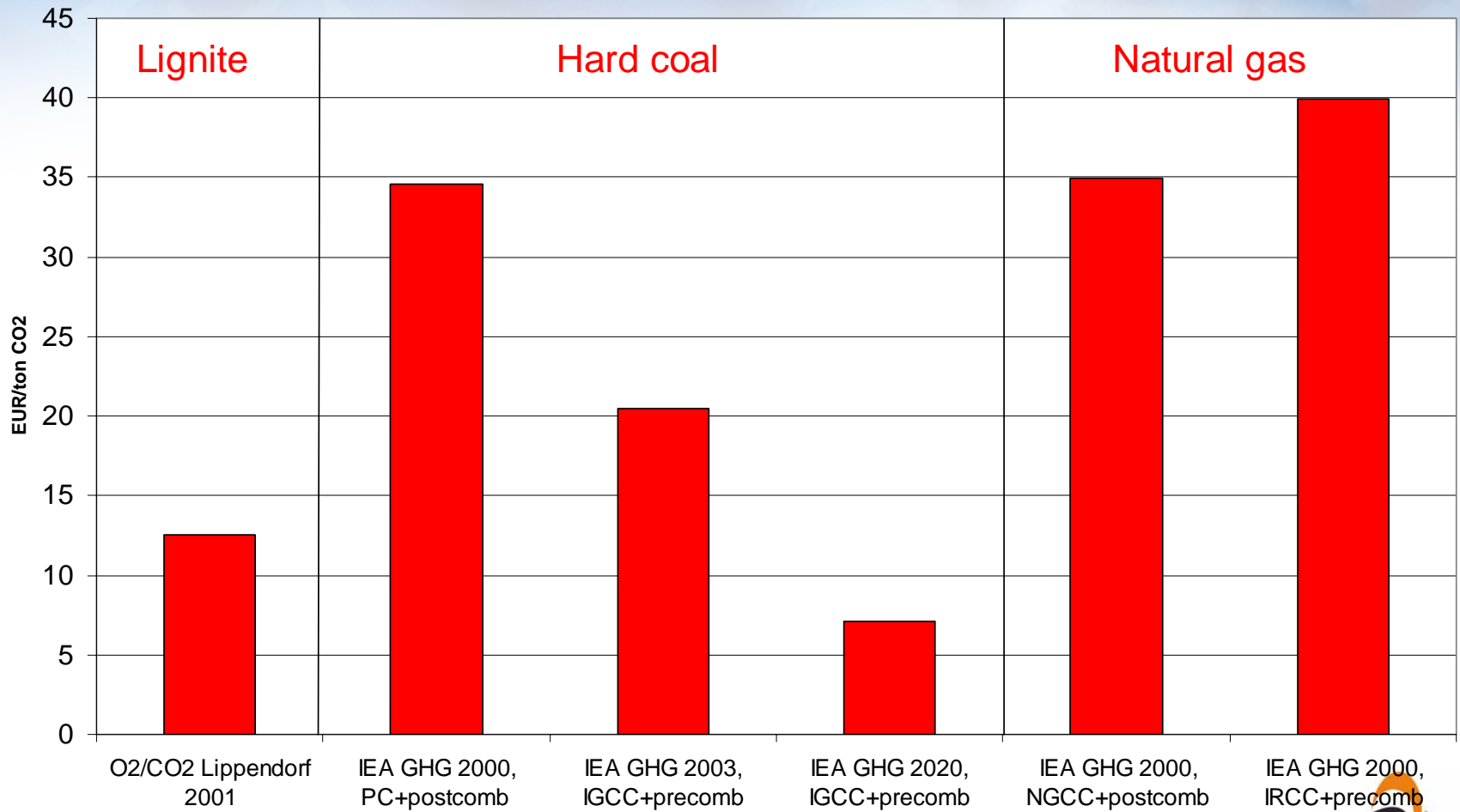
Energy flow diagram for lignite fired plant with O₂/CO₂ combustion



Identified Impacts for Retrofit

- ASU + CO₂ compression reduces overall efficiency by ~ 9%
- Reduces sent out electricity by ~ 18 - 20%
- Air leakage, for reduced pressure operation, increases impacts

CO₂ avoidance cost, transport and storage excluded



Rate of return: 7%; Depreciation time 25 years; Operational time 7500 h/year

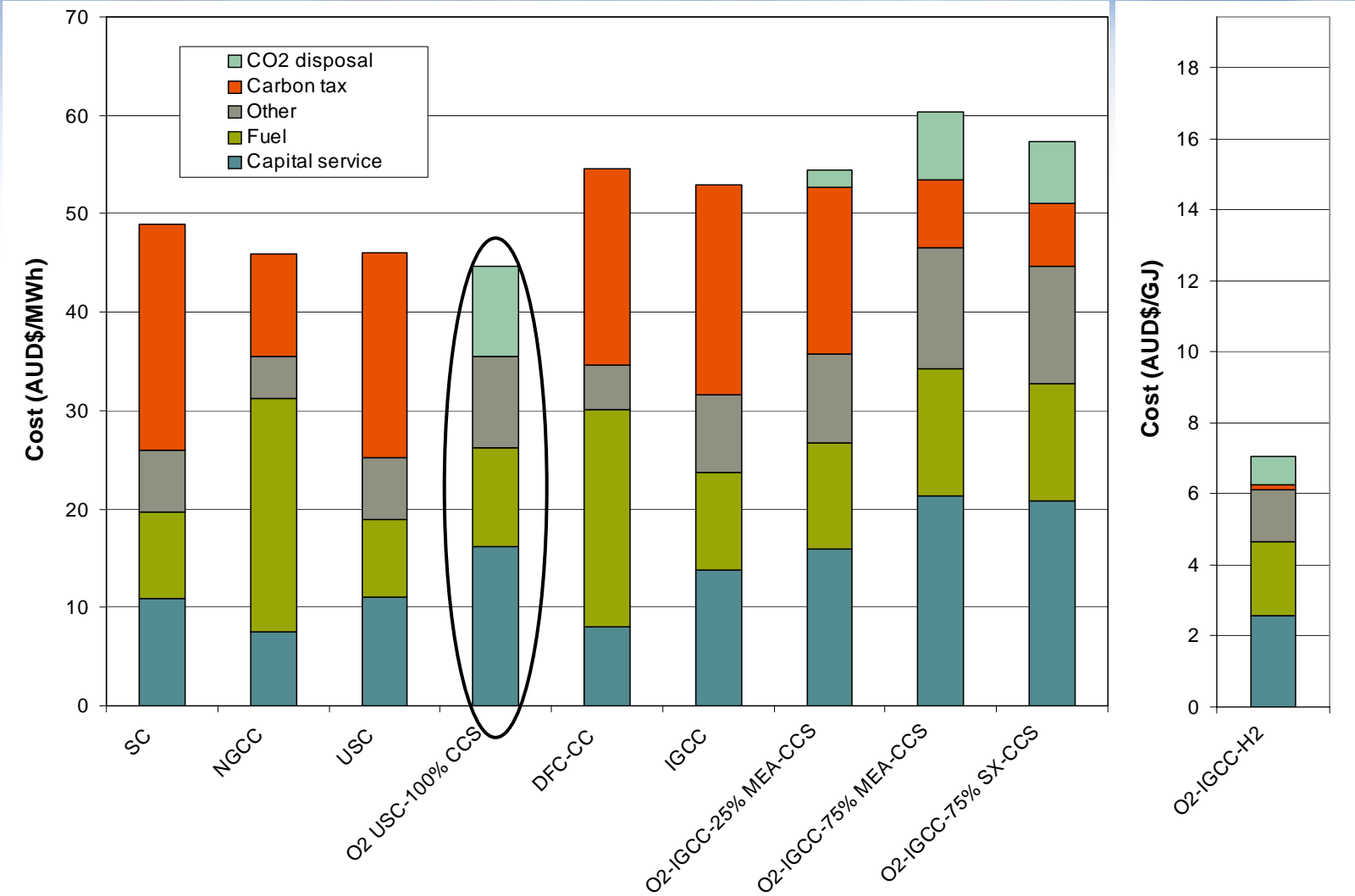


Assessment 4

Report "Systems assessment of future electricity generation options for Australia",
BHPBilliton Group, November 2003

CCSD Australia Compares technology options for
sequestration ready CO₂
for new plants

A5 - CCSD Australia new plant - COE



Cost of CO₂ abatement relative to USC

Technology	Cost of CO ₂ abatement (\$/t CO ₂)
IGCC	182
DCF-CCGT	105
IGCC-25% CCS	86
IGCC-75% MEA-CCS	64
O ₂ -USC-100% CCS	29
NGCC	25
USC	9

Conclusions from assessments



- The assessment studies have shown that
- CCS (includes pipelining) reduces efficiency by 6-10%, and increase generation costs by around A\$20/MWh.
- IGCC generation costs, with or without sequestration, are predicted to be significantly higher than most other technology combinations, for carbon taxes below A\$50/t CO₂.
- **O₂-USC with sequestration gives overall better economics than for IGCC**



Australian Initiatives – Coal21

Japan-Australia Oxy-Fired PF Feasibility Study - 2004



Retrofit with oxygen plant, CO₂ compression and sequestration (including combustion and heat transfer evaluation)

Stage 1 – Detailed engineering feasibility study on the technical requirements and costs to convert an existing PF boiler (Callide A 30 MWe Unit owned by CS Energy) to oxy-firing. Completed Mar 06

Stage 2 – Establishment of an oxy-fired PF demonstration plant capable of producing up to 200,000 tpa of CO₂ for sequestration

Fundamental Research at University of Newcastle

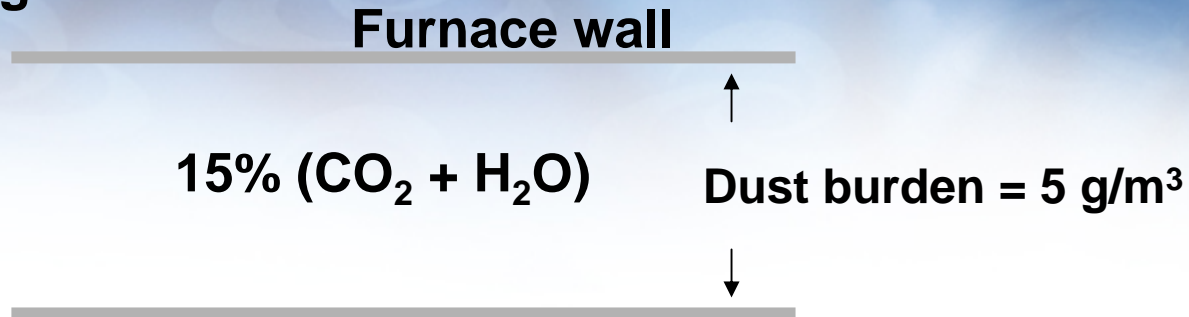


- Heat transfer – radiative
- Combustion – burnout and excess air

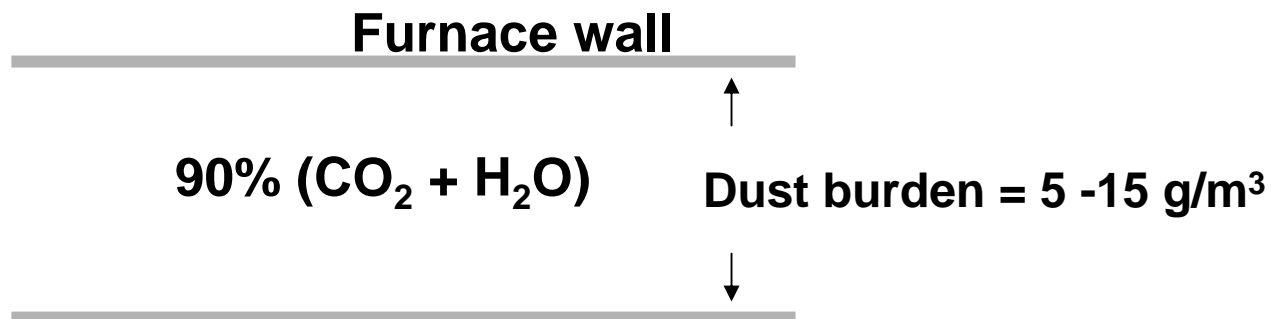
Radiative Heat Transfer



Case-I: Air-Firing



Case-II: Oxy-Firing



3-gray gas model

Article: T.F.Smith et al (1982)



Total emissivity of gray gases:

$$\varepsilon = \sum_{i=0}^I a_{\varepsilon,i}(T) \left[1 - e^{-k_i PS} \right]$$

$$a_{\varepsilon,i} = \sum_{j=1}^J b_{\varepsilon,i,j} T^{j-1}$$

Optimized values for:

$i = 3$ (no. of gray gases)

$j = 4$ (polynomial order)

Where,

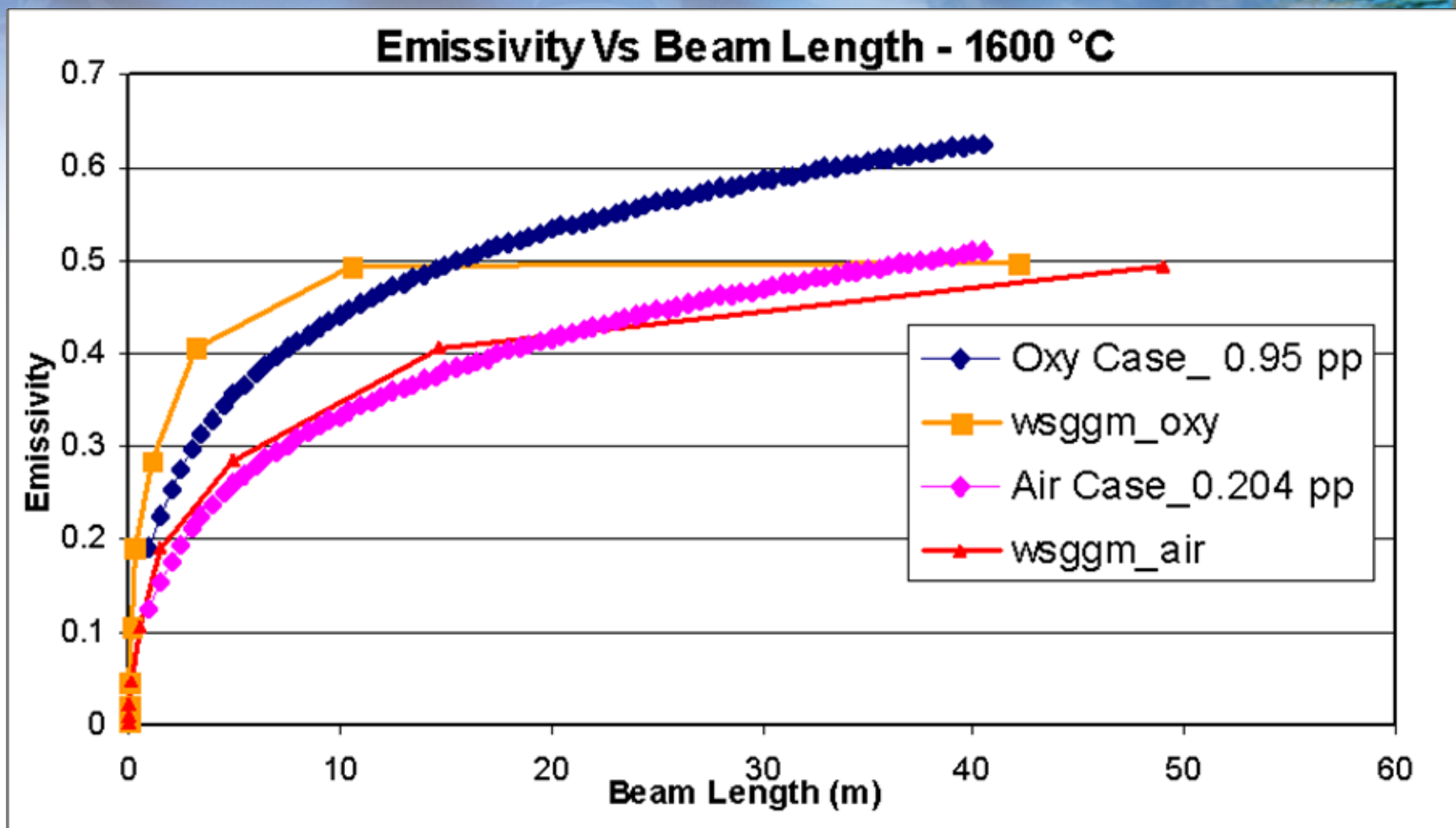
$a_{\varepsilon,i}$ = i^{th} gray gas emissivity weighting factors

$\left[1 - e^{-k_i PS} \right]$ = i^{th} gray gas emissivity with absorption coefficient k_i

PS = (Partial pressure * Path Length) of absorbing gas

$b_{\varepsilon,i,j}$ = emissivity gas temperature polynomial coefficients

WBM Vs WSGGM Model for BL @ 1600 °C



Absorption Spectra

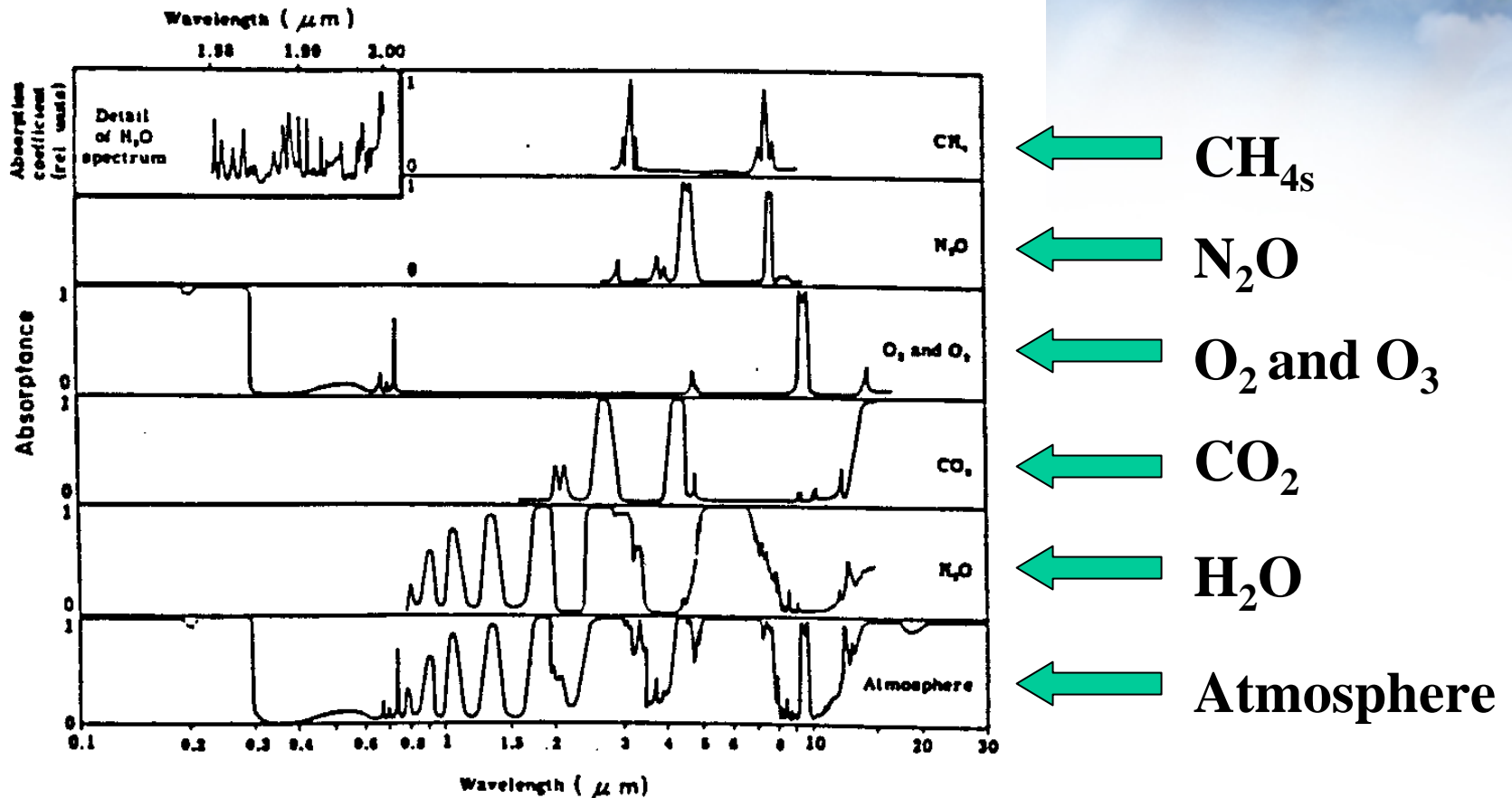
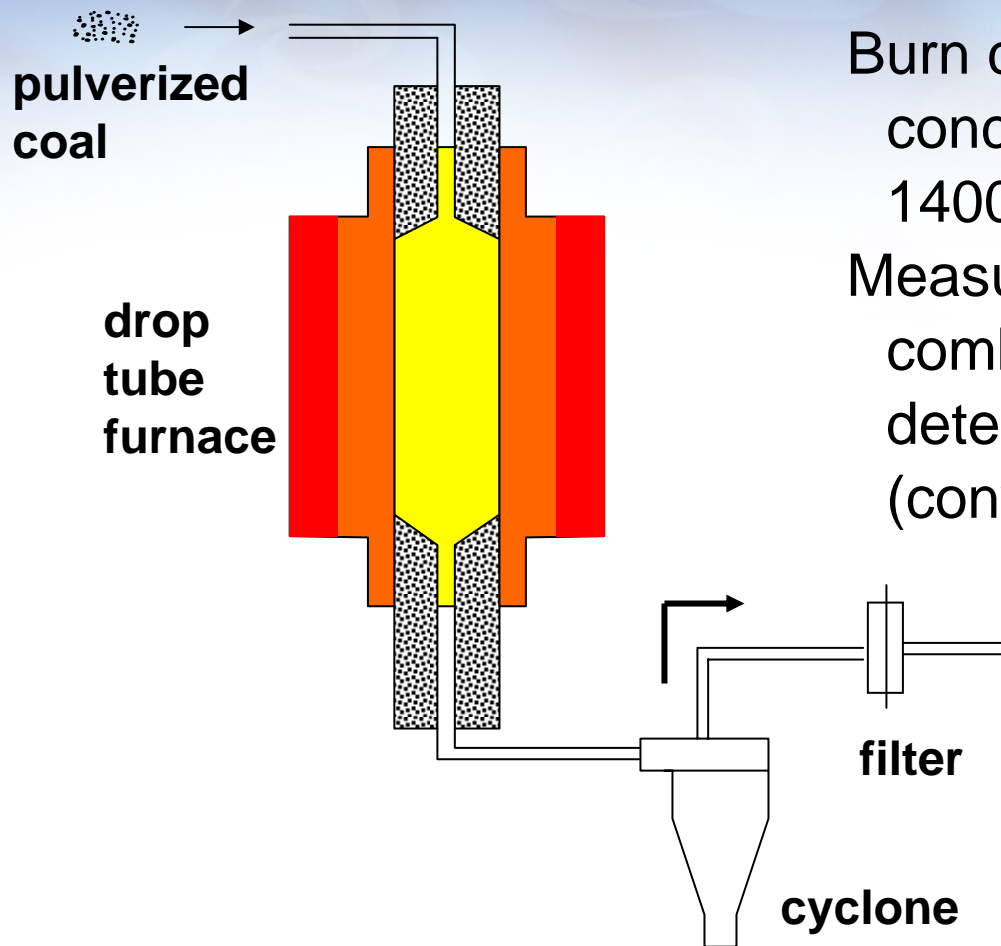


FIG. 5.13. Absorption spectra for H₂O, CO₂, O₂, N₂O, CH₄ and the absorption spectrum of the atmosphere

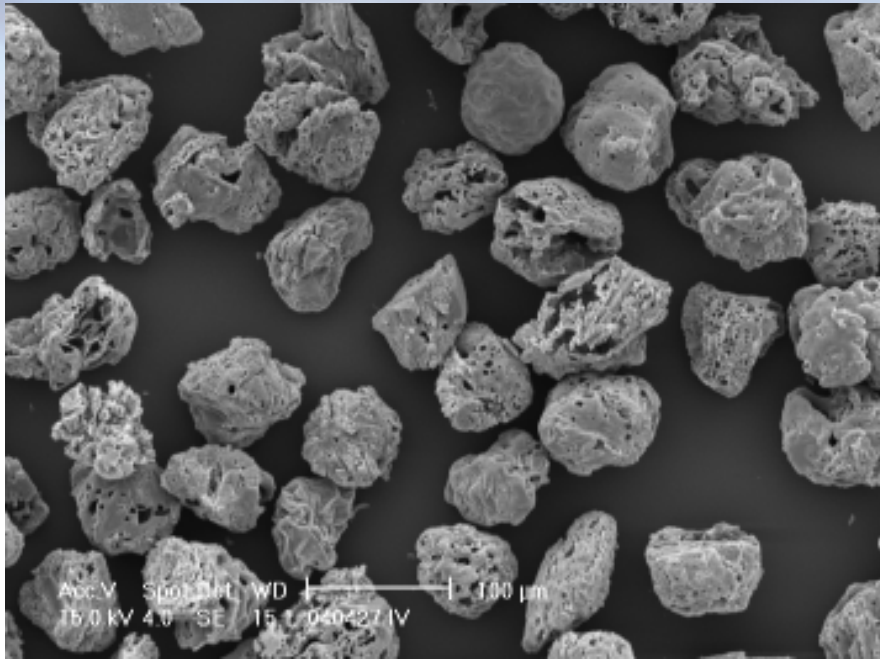
From Fleagle and Businger (1980), An Introduction to Atmospheric Physics

Experiments: Astro DTF

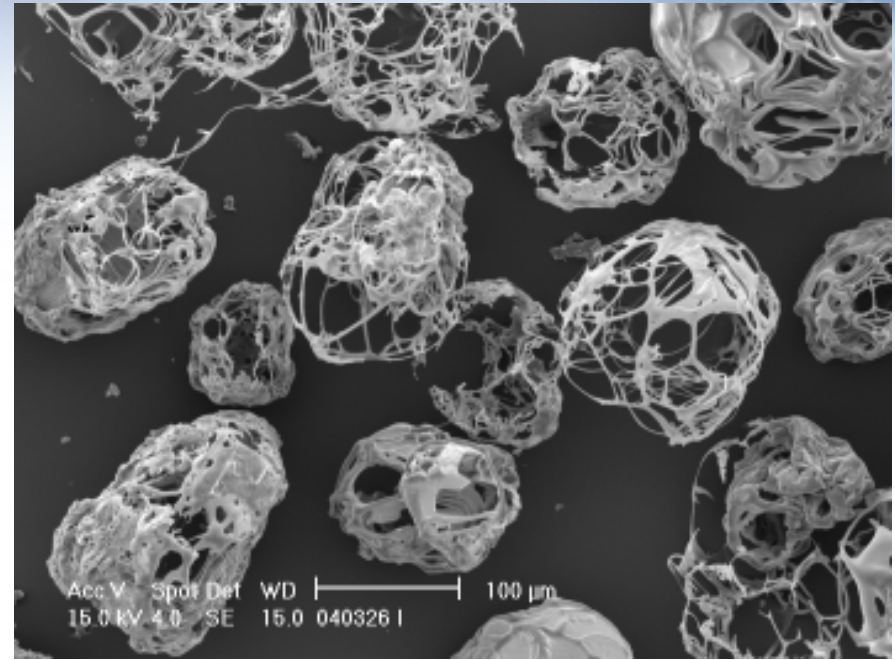


Burn coal in varying oxygen concentrations in DTF at 1400 °C,
Measure carbon burnout from combustion residue to determine reactivity (conversion)

Devolatilisation CRC 272 SEM



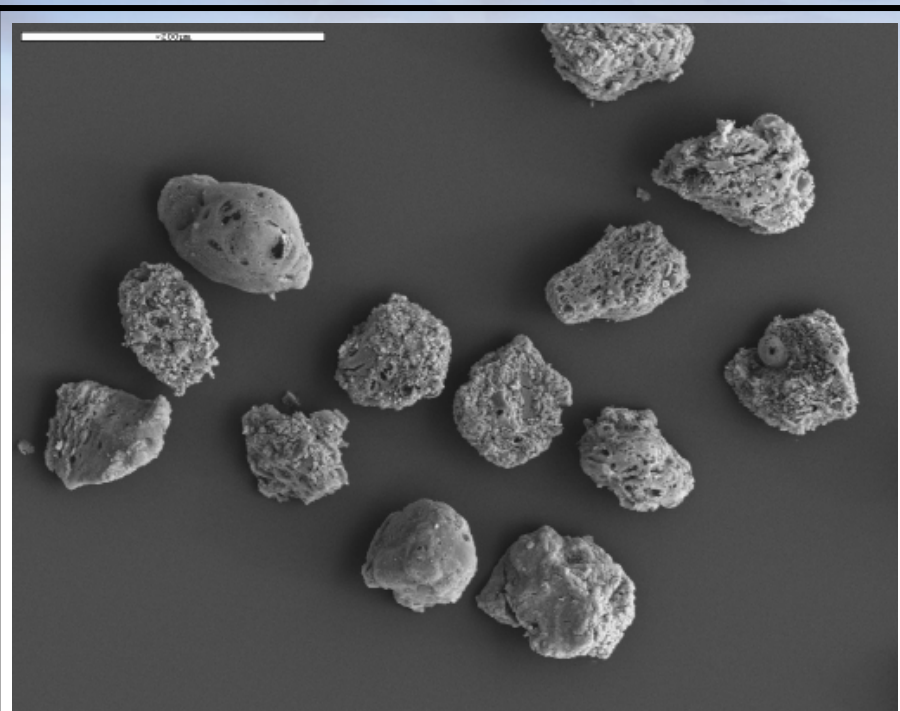
Combustion in 4.6% O₂ in CO₂,
76.2% carbon in sample



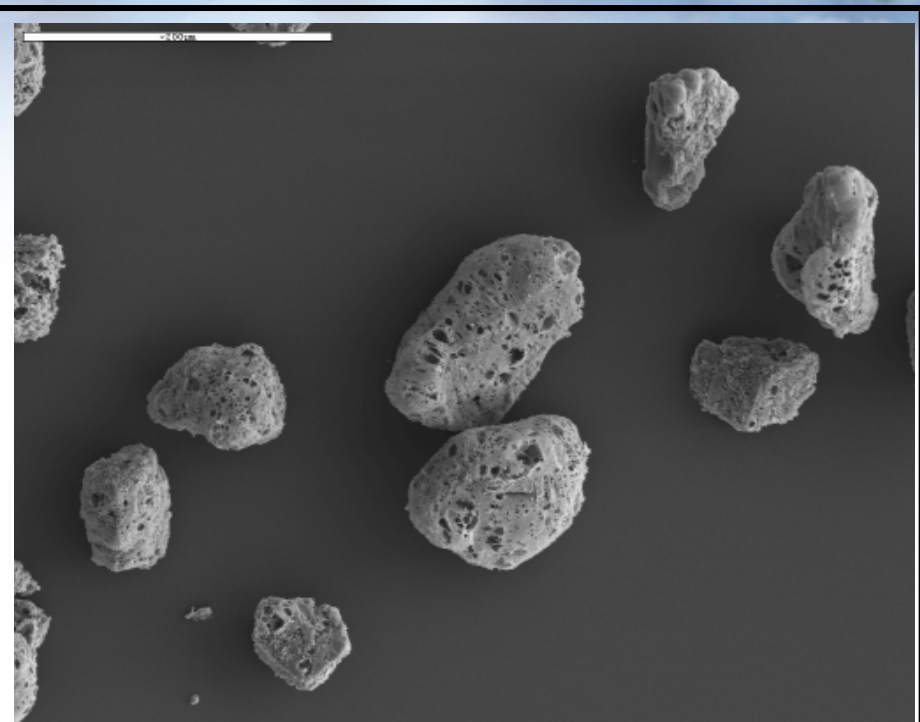
Combustion in 3% O₂ in N₂
82.8% carbon in sample

High VM (35%)Coal

Devolatilisation CRC 299 SEM



Char formed in CO₂



Char formed in N₂

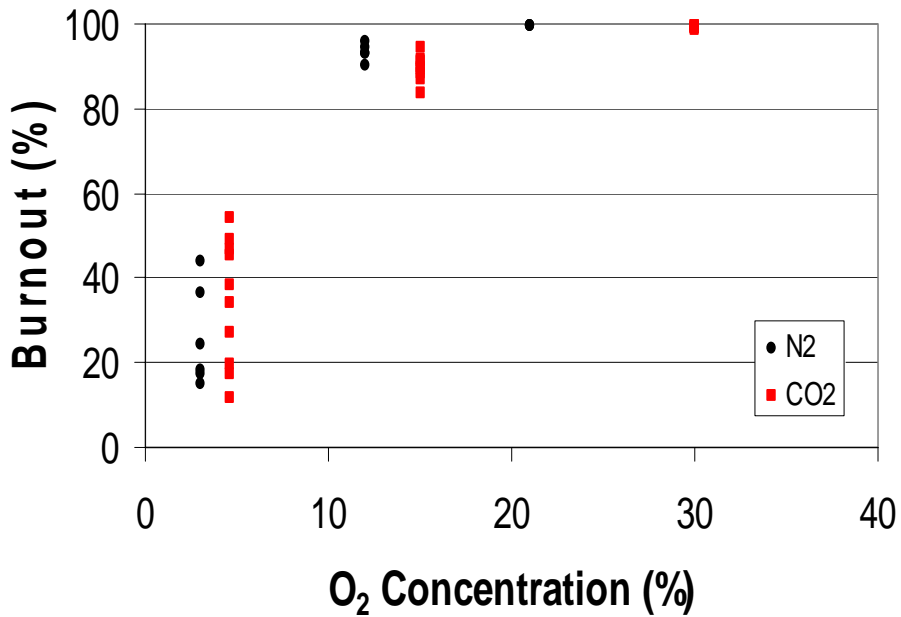
Low VM (24%)Coal

Experimental Results for Combustion



Conversion of Fixed Carbon

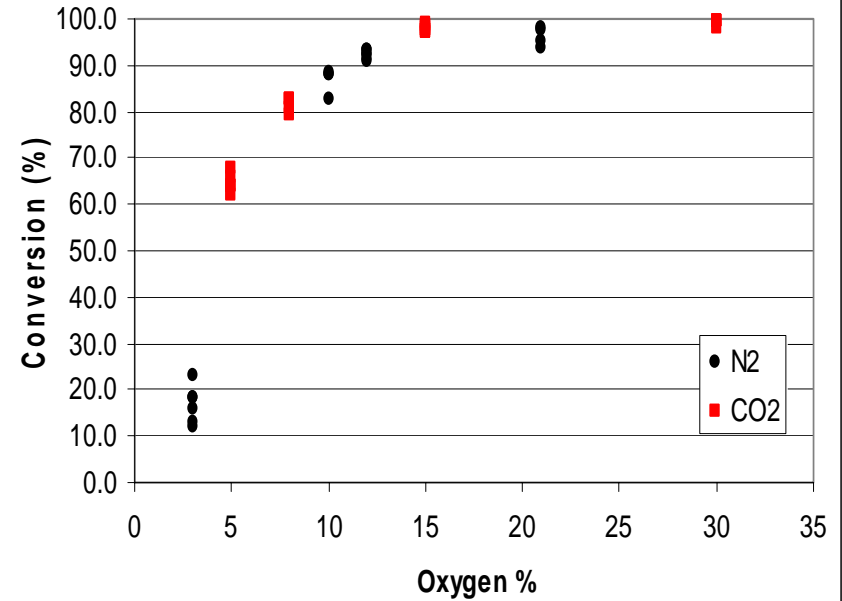
CRC 272, zeropoint determined by V*



CRC 272

Conversion of Fixed Carbon

CRC 299, Zeropoint determined by V*



CRC 299



Future Challenges



Technological developments needed in

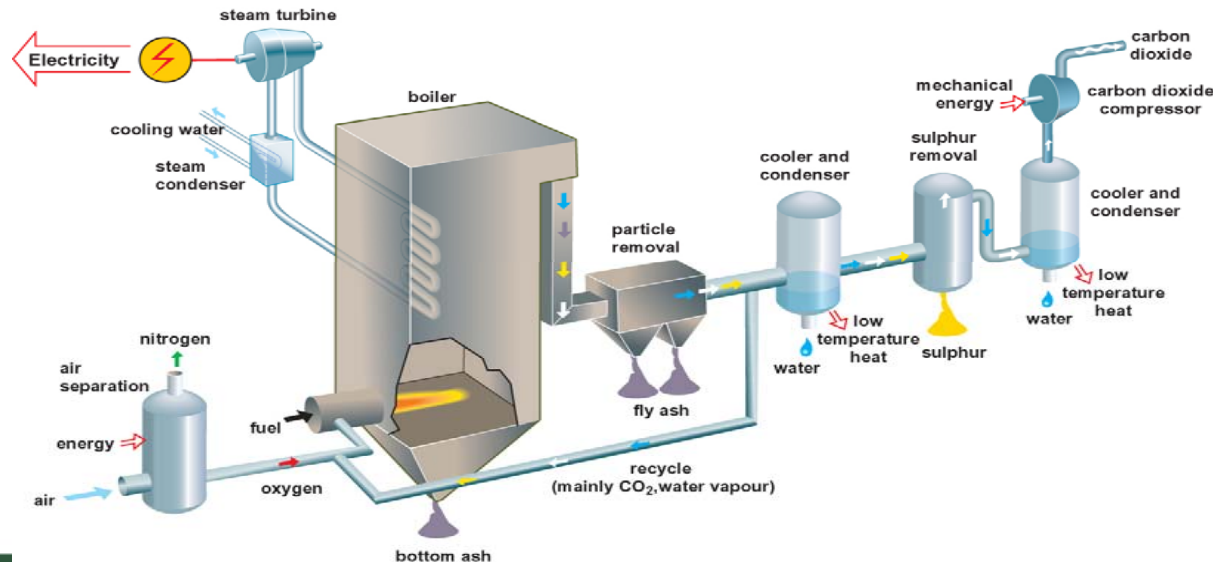
New Boilers - less or nil recycle

Air Separation – new technology – scale up

CO₂ – clean-up – tolerance for SO_x, NO_x – removal of SCR

Challenge 1: Boiler design

- Design of next generation oxyfuel boiler, combustion considerations
- Reduced recycle rate or complete removal of recycle
- Optimisation of combustion for reduced formation of NO_x , to eliminate catalytic reactors



Challenge 2: O₂ Production



At present cryogenic air separation only technology for large scale oxygen production; issues:

- Scale-up
- Optimal integration in power plant
- Oxygen purity optimisation: where to remove the non-condensables?
- Emerging technologies?
- High temperature oxygen separation with ceramic materials, e.g. oxygen transfer membranes: Scale-up and cost? Integration into power plant

Challenge 3: CO₂ Processing



- NO_x control needed?
- Flue gas desulphurisation needed?
- Flue gas condensing
- Design of CO₂ compression train depending on CO₂ impurity level:
 - Dehydration & Removal of non-condensable
 - Requirements on CO₂ purity from transport, storage environmental perspective is generally unexplored
 - Behaviour of CO₂ with impurities at high pressures (supercritical) is not well known (solubility etc.)

SUMMARY



All pilot scale tests demonstrate technical feasibility

All assessment studies demonstrate economic feasibility

Fundamental research in radiative transfer and combustion kinetics in new environment

Technological innovations needed in new boiler design, large scale ASU or Chemical Looping and compression of CO₂ with some level of impurities

Acknowledgements



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