International Oxy-Combustion Research Network for CO_2 Capture

Report on Inaugural (1st) Workshop

Report Number: 2006/4

Date: July 2006

INTERNATIONAL ENERGY AGENCY

The International Energy Agency (IEA) was established in 1974 within the framework of the Organisation for Economic Co-operation and Development (OECD) to implement an international energy programme. The IEA fosters co-operation amongst its 26 member countries and the European Commission, and with the other countries, in order to increase energy security by improved efficiency of energy use, development of alternative energy sources and research, development and demonstration on matters of energy supply and use. This is achieved through a series of collaborative activities, organised under more than 40 Implementing Agreements. These agreements cover more than 200 individual items of research, development and demonstration. The IEA Greenhouse Gas R&D Programme is one of these Implementing Agreements.

DISCLAIMER

ACKNOWLEDGEMENTS AND CITATIONS

The IEA Greenhouse Gas R&D Programme supports and operates a number of international research networks. This report presents the results of a workshop held by one of these international research networks. The report was prepared by the IEA Greenhouse Gas R&D Programme as a record of the events of that workshop.

The International Research Network on Oxy-Combustion is organised by IEA Greenhouse Gas R&D Programme. The organisers acknowledge the hospitality provided by the hosts:

VATTENFALL

The report should be cited in literature as follows:

IEA Greenhouse Gas R&D Programme (IEA GHG), "International Oxy-Combustion Research Network for CO_2 Capture: Report on Inaugural (1st) Workshop", 2006/4, July 2006.

Further information on the network activities or copies of the report can be obtained by contacting the IEA GHG Programme at:

IEA Greenhouse R&D Programme, Orchard Business Centre, Stoke Orchard, Cheltenham Glos. GL52 7RZ. UK
Tel: +44 1242 680753 Fax: +44 1242 680758
E-mail: mail@ieaghg.org
Website: www.ieagreen.org.uk

International Oxy-Combustion Research Network for CO_2 Capture

Report on Inaugural (1st) Workshop

Vattenfall Europe Mining and Generation
Cottbus, Germany

29th and 30th November 2005

An afternoon visit to the
Schwarze Pumpe Power Station

This workshop is organised by IEA Greenhouse Gas R&D Programme
with the support of Vattenfall AB.

INTERNATIONAL OXY-COMBUSTION NETWORK FOR CO_2 CAPTURE
Report on 1st Workshop

Vattenfall Europe Generation and Mining AG
Cottbus, Germany

29th and 30th November 2005

1. INTRODUCTION

This report summarises the presentations of the inaugural workshop on International Oxy-Combustion Network for CO_2 Capture that was organised by IEA Greenhouse Gas R&D Programme and was hosted by Vattenfall AB.

The workshop was held at the head office of Vattenfall Europe Generation and Mining AG in Cottbus, Germany on the 29th and 30th of November 2005. A visit to the Schwarze Pumpe Power Station, one of the world's most advanced lignite power plant and the future site of the 30MW Oxy-Coal Combustion Pilot Plant, was arranged in the afternoon of the 29th of November.

IEAGHG would like to acknowledge and thank Prof. Lars Strömberg of Vattenfall AB for his full support to this workshop.

2. NETWORK OVERVIEW

Carbon dioxide capture and storage is now included in most OECD countries' energy policies and R&D programmes as one of the strategies to mitigate carbon dioxide emissions from large emitters. One of the leading carbon capture technology considered for power generation industry is the use of oxy-fuel combustion technique.

In recognition to the different efforts by the industry, academe and research institutes to demonstrate the techno-economic feasibility of this technology as carbon capture option for a power plant in the near future; IEA Greenhouse Gas has initiated the establishment of the International Network for Oxy-Fuel Combustion.

The aim of this Network for Oxy-Fuel Combustion is to provide an international forum for organisations with interest in the development of Oxy-Fuel Combustion Technology.

Due to the broadness of this topic, it was decided to focus the theme of the first workshop on the "Oxy-Fuel Combustion for Coal Fired Power Plant". Nevertheless, the future workshop will also attend to the development in Oxy-Fuel Combustion for Gas Fired Power Plants and other novel oxy-combustion processes.

3. WORKSHOP ATTENDEES

The workshop brought together 64 participants from the power generation industries, boiler and combustion equipment manufacturers, oxygen production and CO_2 processing industries, research institutes and universities covering 17 countries worldwide. The workshop has been over-subscribed with 20 other potential participants in the waiting list. The attendance list is given in Appendix 1.

4. WORKSHOP PROGRAMME AND HIGHLIGHTS

The agenda is given in Pages 3 and 4. Over the 1 ½ days, the workshop covered the following topics:

- Technology Benchmarking and Modelling Studies – A Review of the Oxy-Fuel Combustion R&D Activities.

- Work-in- Progress, Development in Oxy-Fuel Combustion Studies.

- Oxygen Production and CO_2 Processing – Overview to the Different R&D Activities for Power Generation Industry.

- An Overview, Progress and Development in Large Scale Oxy-Fuel Combustion Project

The theme of the first meeting focused on the "Development of the Oxy-Combustion Technology for Coal Fired Power Plant" featuring an update to the progress in the development of large scale oxy-coal combustion pilot plant studies currently on-going in Europe and Australia.

The workshop started with the welcome address given by Mr. Reinhardt Hassa, Member of the Management. Board, Vattenfall Europe Mining and Generation AG. He discussed about the role of Vattenfall Europe Mining and Generation its role in the power generation sector in Germany and their commitment toward sustainability and clean environment.

This is followed by welcome address by Dr. John Topper, presenting the role of IEA Greenhouse Gas R&D Programme in establishing this network, its role and the objectives of the meeting. He clearly stressed the importance of obtaining feedback from the participants firstly to enhance communications to develop collaborative action toward the deployment of carbon capture and storage technology.

A keynote presentation was given by Prof. Keiji Makino, chief executive engineer of IHI, who is also one of the pioneers in the development of this technology in Japan which started in 1990s. He presented an overview of the different Oxy-Coal Combustion R&D activities carried out in Japan. He clearly noted the important role of coal in the power generation sector of Japan and highlights the potential of this technology for retrofitting existing coal fired power plants. He also provided a good insight to the technical background and feasibility study currently on-going in co-operation with the Australian consortium under the Callide-A project. A summary of his presentation was presented in succeeding section.

A total of 13 other presentations were made during the one and half day meeting. Also included was a plant visit to the Schwarze Pumpe Power Station, the future site of the 30MW Oxy-Combustion Pilot Plant with a plan to commission the facility by 2008. Figure 1 shows the proposed location of the pilot plant within the premise of the power station.

Prof. Lars Stromberg and Mr. Uwe Burchardt provided an insight to the background and programme of the 30 MW Pilot Plant study of Vattenfall. Prof. Stromberg stressed the importance of reliability and availability of the power generation plant as one of the primary reasons to proceed with their study.

Inaugural Workshop

Oxy-Fuel Combustion Research Network

Vattenfall Europe Mining and Generation AG Head Office
Vom Stein Strasse 39
Cottbus, Germany

29th and 30th November 2005

Day 1 – Outline Agenda

0900 - 0930	**Welcome Address - Vattenfall Europe Mining & Generation: The Backbone of the Energy Group** Reinhardt Hassa, Member of the Mgmt. Board, Vattenfall Europe Mining and Generation AG
	IEA Greenhouse Gas R&D Programme: Background and Introduction to Oxy-Coal Network John Topper, Managing Director, IEA Environmental Project Ltd.
0930 – 1030	**Overview of the Oxy-Fuel Combustion Studies in Japan** Keiji Makino, Chief Executive Engineer, IHI, Japan
1030 – 1045	Coffee Break

Technology Benchmarking and Modelling Studies: Review of the Oxy-Fuel Combustion R&D Activities

Session Chairman: John Topper, IEA Greenhouse Gas R&D Programme, UK

1045 – 1115	**Oxy-Fuel Combustion Application for Coal Fired Power Plant: What is the Current State of Knowledge…** Stanley Santos, IEA Greenhouse Gas R&D Programme, UK
1115 – 1145	**Fundamentals of Oxy-Fuel Combustion** Prof. Terry Wall, University of Newcastle, Australia
1145 – 1215	**Technology Choice and Benchmarking Studies** Prof. Lars Stromberg, Vattenfall, Sweden
1215 – 1300	Lunch
1330 – 1515	**SCHWARZE PUMPE POWER STATION: Plant Visit & Grp. Photo** Co-ordinated by Vattenfall Europe AG
	Coffee Break

Development in Oxy-Fuel Combustion Studies: Work in Progress

Session Chairman: Prof. Klaus Hein, University of Stuttgart, Germany

1515 – 1545	**Vattenfall's Activities on Oxy-Fuel Combustion Studies** Prof. Lars Stromberg, Vattenfall, Sweden
1545 – 1615	**An Overview of Oxy-Fuel Combustion R&D Programme in CANMET** Kourosh Zanganeh, CANMET, Canada
1615 – 1645	**Fundamental Oxy-Fuel Combustion Research Carried Out within the ENCAP Project** Klas Anderson, Chalmers University, Sweden
1645 – 1715	**Development in Oxy-Coal Combustion Boiler: A View from Boiler Manufacturer** Timo Hyppänen, Foster Wheeler Oy, Finland
1930	**Workshop Dinner**

DAY2 – Outline Agenda

0845 – 0900	**Opening of Day 2 Sessions** Review of the Progress of the Workshop

O2 Production and CO2 Processing
Overview of R&D Activities for Power Generation Industry
Session Chairman: Roger Dudill, Air Products, UK

0900 – 0915	**Air Liquide Air Separation Units – Mastering Design and Operations** Guillaume de Souza, Air Liquide, France
0915 - 0930	**Oxy-Combustion for CO_2 Capture in Pulverized Coal Boilers** Guillaume de Smedt and Guillaume de Souza, Air Liquide, France
0930 – 1000	**Capturing CO_2 from Oxy-Fuel Combustion Flue Gas** Minish Shah, Praxair, USA
1000 – 1015	Coffee Break

An Overview, Progress and Development in
Large Scale Oxy-Fuel Combustion Project
Session Chairman: Sho Kobayashi, Praxair, USA

1015 – 1030	**Vattenfall Oxy-fuel Pilot Plant Study – Programme Overview** Uwe Burchardt, Vattenfall Europe Generation and Mining, Germany
1030 – 1115	**Australian Japanese Co-operation on OxyFuel Pilot Project for Plant Retrofit – Callide-A Project** Chris Spero, CSEnergy, Australia
1115 – 1230	**Discussion Forum** Session 1: Boiler and Burner Development – Future R&D Requirements Session 2: Development in O_2 Production and CO_2 Processing – Requirements for Energy & Cost Reduction.
1230 – 1245	**Closing Session** Wrapping Up and Future Activities
1245 – 1400	Lunch

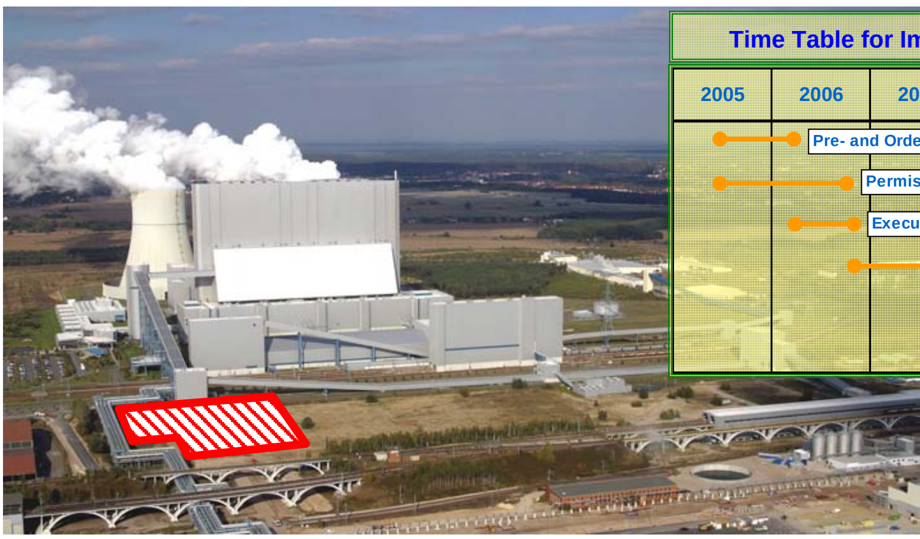
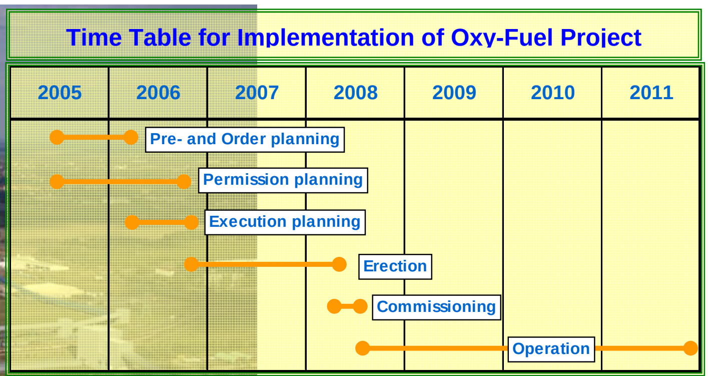



Figure 1: Proposed site for the $30MW_{th}$ Oxy-Coal Pilot Plant in Schwarze Pumpe Power Station. (Picture courtesy of Vattenfall)

Dr. Chris Sphero presented an overview to the programme of the Callide-A Project. This project as mentioned earlier is the Australian-Japanese cooperation looking at the different aspects of retrofitting a coal fired power plant with an oxy-combustion boiler. He also highlighted the proximity of the Callide–A Power Station to a potential CO_2 storage site. Figure 2 presents the 25MWe Callide–A Power Plant and the geographical location showing the proximity to CO_2 storage site.

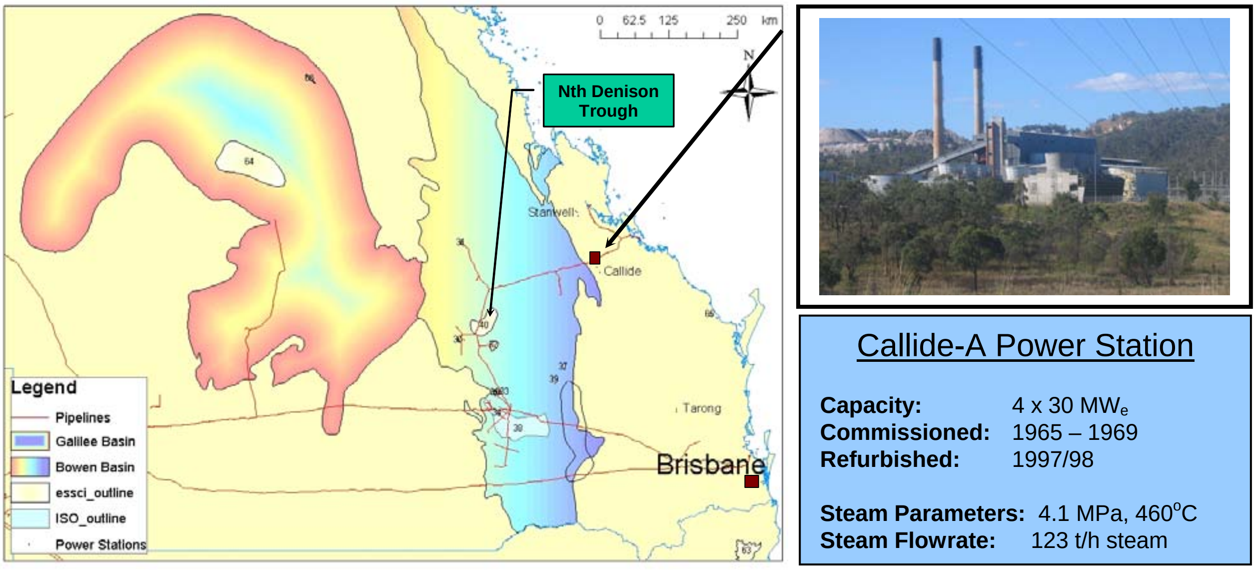


Figure 2: Location of Callide-A Project. A Planned retrofit to a coal fired power plant with an oxy-combustion boiler

The workshop also provided the opportunity to look at the development of the Oxy-Coal Combustion Technology from the boiler manufacturer's point of view. This was presented by Dr. Timo Hypannen of Foster Wheeler Oy. A view in the development of oxygen production was presented by Mr. Guillaume de Souza of Air Liquide. The impact and technical issues on the processing of a CO_2 rich flue gas in relation to the operation of the oxy-coal combustion boiler was presented by Dr. Minish Shah of Praxair.

With regard to on-going studies, Dr. Klas Anderson presented some of the results gathered from the studies undertaken by Chalmers and Stuttgart University with regard to combustion and radiation properties. Dr. Kourosh Zanganeh provided an overview of the works done by CANMET. Mr. Guillaume de Smedt of Air Liquide presented an insight to their work in-cooperation with Babcock & Wilcox.

The final agenda of the workshop was on the discussion of various issues. IEAGHG in co-operation with Prof. Terry Walls of Newcastle University released an issue paper during the meeting which was used as a guide for the discussion which was led by Dr. Sho Kobayashi of Praxair.

The issue paper covers four general topics including:

- Boiler and burner development
- Plant operation and safety
- O_2 production
- CO_2 rich flue gas processing and compression.

The issue paper is included in the Appendix. IEAGHG will still welcome any additional comments or reaction to the issue paper.

5. PRESENTATION SUMMARY

5.1. Overview of the Oxy-Fuel Combustion Studies in Japan
Prof. Keiji Makino, Chief Executive Engineer, IHI

Since the early part of the 1990s, Japan has been active in the development of oxy-coal combustion with recycled flue gas for the purpose of investigating its viability for plant retrofit suitable for capturing CO_2. This presentation provided a good overview to the work done under the NEDO programme during the last 15 years, the results of the current research activities, and the introduction to the Australian-Japanese co-operation under the Callide-A Project.

Specifically, this presentation discussed the following points:

- Japanese strategy for CO_2 Reduction
- Oxy-firing studies in Japan
- Study of 1000 MW oxy-firing super critical unit
- Japan-Australia oxy-firing project

The presentation briefly explained the strategy undertaken by the Japanese government in dealing with the challenges of reducing CO_2 and maintaining energy security. Under the Kyoto Protocol, Japan is required to reduce 6% of their overall greenhouse gas emissions. At the same time, the government also recognises the role of coal and its importance to the energy security of Japan. Thus, the government has initiated the Clean Coal Cycle (C3) initiatives with the following key objectives:

(a.) To promote and develop innovative clean coal technologies.
(b.) To demonstrate other diversified clean coal technologies.

Under the first objective of C3 initiatives covers the development of oxy-fuel combustion boiler for plant retrofit. In the past 20 years, IHI has initiated various fundamental studies in Japan and this covers the following:

- Study on ignition and flame propagation.
- Fundamental study on oxy-firing (experimental work done by Tokyo Institute of Technology - TIT)
- In-furnace desulfurisation study of oxy-firing (also undertaken by TIT)
- 1.2 MW Combustion test
- CO_2 compression demonstration test

From these fundamental studies, the presentation summarised the following results:

- Ignition and flame propagation study was undertaken using small gravity test. Results have indicated that ignition and flame propagation was shown to be slower in the O_2/CO_2 environment as compared to that of the O_2/N_2 environment.
- Fundamental study undertaken by Tokyo Institute of Technology covers the investigation of NOx formation and reduction mechanisms of oxy-combustion with recycled flue gas.
- The study by Tokyo Institute of Technology also investigated the mechanism for in-furnace desulphurisation of oxy-firing combustion based on $CaCO_3$ injection.
- IHI undertaken a pilot scale combustion test of oxy-coal combustion with recycled flue gas using their 1.2MW test rigs. This covers various in-flame measurements looking at the combustion characteristics of two different types of burners and their pollution

emissions. Unique to this study is their in-flame measurements taken for NH_3 and HCN in attempt to understand NOx formation mechanism in an industrial scale boiler.
- The study led by IHI during the 1990s also involves the demonstration of liquefaction of flue gas. One of the aims of this study was to demonstrate the viability of connecting compression equipment to the boiler. CO_2 was successfully recovered under 0^oC and a 7MPa condition was noted.

The fundamental experimental studies described above were complimented by simulation study of 1000MW class oxy-firing advanced super critical unit. Primary results presented in these work include the attempt to understand the dynamic operation of a 1000MW power plant operating with an air separation unit and flue gas compression.

Finally, the presentation concludes with an introduction to the Australian-Japanese cooperation under the Callide-A project. The overall schedule for this project was presented. It was aimed to demonstrate how to retrofit the 30MWe oxy-coal firing boiler by 2006-2010.

5.2. Oxy-fuel Combustion Application for Coal Fired Power Plant: What is the…
Stanley Santos, IEA Greenhouse Gas R&D Programme

The results of the techno-economic study commissioned by IEA Greenhouse Gas R&D Programme on Oxy-Combustion for Coal Fired Power plant were presented. This study (IEAGHG Report No. 2005/9) was undertaken by Mitsui Babcock Energy Ltd. in co-operation with Air Products and Alstom Power. The report consists of study for both natural gas fired and coal fired power plant based on oxy-combustion capture processes; however, only the results for the coal fired case were presented.

The results of the study indicated an energy efficiency penalty of 8% as compared to reference conventional coal fired power plant operating with advanced supercritical steam and equipped with SCR and FGD.

The second part of the presentation presented an overview to the early works done on Oxy-Coal Combustion pilot scale study. This includes the an overview to the study done by:
- Argonne National Laboratory – which include some results gathered from the 115 kW pilot scale experiment of Battelle and 3 MW pilot scale test of EERC.
- International Flame Research Foundation (3 MW)
- Mitsui Babcock Energy Ltd. (120 kW)
- International Combustion Ltd. (35 MW)

Various key issues were raised regarding the development in boilers and burners and these include:
- Effect of recycled flue gas to the heat transfer profile of the boiler
- Effect of recycled flue gas to the ash deposition
- Requirements for coal characterisation (devolatilisation and char combustion)
- Issue regarding the air-ingress, start-up, turn down operation, and O_2 handling

5.3. Fundamentals of Oxy-Fuel Combustion
Prof. Terry Wall, University of Newcastle

The fundamental principles of oxy-coal combustion with recycle flue gas were explained. The following issues were discussed in detail:
- Pollutant emissions – including key results from various work on NOx and SO2.

- Heat Transfer – which include the impact of recycle flue gas to the radiative and convective heat transfer
- Reactivity of coal under a $O_2/CO_2/H_2O$ environment
- Mathematical modelling for furnace operating in oxy-combustion with recycled flue gas

The presentation explained how the mathematical model for furnace firing in oxy-combustion mode was developed. Specifically, it was noted that the significant difference in the adsorption and emission spectra for triatomic gases. This implies that combustion environment for oxy-combustion will have a higher emissivity. The radiation model was developed based on band model.

The mechanisms for NOx formation were explained. This is based on the results undertaken by Okazaki's research during the 1990s. The potential for increase in sulfur capture efficiency was also noted. The increase in desulfurisation efficiency was attributed to the inhibition of $CaSO_4$ decomposition at higher temperature (> 1500K) and increase in recycled flue gas at the intermediate temperature (< 1450 K).

5.4. Technology Choice and Benchmarking Studies
Prof. Lars Strömberg, Vattenfall AB

The point of view of Vattenfall choosing Oxy-Coal Combustion for further development and validation as their choice of technology for CO_2 capture for their power plant was explained. In this regard, it was clearly noted the following:

- Oxy-fuel is currently the technology that provides the least cost within their benchmarking studies.
- It is their view that oxy-combustion is suitable for coal and has little development work required.
- It is their view that it could make good use of their experience with their present fleet of pulverised coal fired power plants.

The benchmarking study done by Vattenfall presented a comprehensive review on the various results on techno-economic studies on CO_2 free power plant published in the literature. The gap and difference among the results presented in various literatures were critically analysed. A specific example was presented showing the big difference in cost analysis among the different studies published was due to higher assumption for their fixed and O&M cost.

Results of their IGCC benchmark study were presented. It was noted that reference IGCC today is not competitive with the current pulverised coal fired power plant. Likewise, it also explained why IGCC has been unfavourable in the point of view of several power generation companies. This is especially stressed on the requirements for high availability which could be easily achieved by PF power plant.

One of the conclusions noted that with CO_2 emission penalty of € 20 per tonne, the competition is between coal power plant with capture and natural gas fired power plant without capture.

5.5. Vattenfall's Activity on Oxy-Fuel Combustion Studies
Prof. Lars Strömberg, Vattenfall AB

The CO_2 free power plant project of Vattenfall was introduced. An overview to the main driver of the current oxy-fuel combustion activities and the $30MW_{th}$ pilot plant study were presented. This project has been active since 2001. It consists of 5 stages and it will end with a proposal of how to build a full size demonstration plant. A pre-engineering phase for the demonstration plant is planned during 2008 – 2010.

The five stages of the project include:

- Phase 0: Is it possible?
- Phase 1: Gap analysis
- Phase 2: Concept development
- Phase 3: Technology development and engineering
- Phase 4: Construction and operation of a demonstration plant.

The technical target for this project was as follows:

- Total cost of capture should achieve below € 20. / tonnes CO2
- Capture efficiency of 95%

Currently, the project is now under Phase 2 which also includes the construction of the pilot plant and various test programmes.

The allocated budget of the pilot plant project was € 37 million for construction of the plant and € 20 million for the test programme. The pilot plant consists of oxy-combustion boiler, gas cleaning, CO_2 processing and cleaning, and air separation unit. Further details to the experimental programme will be presented in Section 5.11.

5.6. An Overview of Oxy-Fuel Combustion R&D Programme in CANMET

Kourosh Zanganeh, CANMET

An overview to the Climate Change Plan of Canada was presented. CCS technology was noted to have an important role in the energy future in the carbon constrained energy economy. In line with Canadian Government programme on zero emission technology, various programme and activities were initiated and one these programme includes the CETC Oxy-Fuel Research Consortium.

The goal consortium is to develop oxy-fuel combustion technologies for improved efficiency and capture of CO_2 from flue gas streams. Under this consortium, research programmes were initiated and currently on-going in the field of:

- Burner development
- Boiler performance simulation
- Multi-pollutant capture integration
- Advance process and cycle development
- Field demonstration of oxy-fuel combustion
- CO_2 capture and compression unit development.

The focus area of the current programme is working toward the development of 2nd generation oxy-fuel combustion systems for power generation. This will be looking at various oxy-fuel combustion developments in boilers and burners and these includes:

- 2nd generation oxy-fuel combustor design and optimisation which will include study on oxy-firing mode with reduced amount or no flue gas recycle.
- Oxy-steam combustion process development
- Advance oxy-fuel and oxy-steam burner design and development.
- Multi-pollutant sorbent for oxy-combustion process
- Zero emission gas turbine combine cycle.

- Novel and efficient CO_2 capture and compression process development, pilot scale unit design and implementation. The programme will also focus on CO_2 capture and compression performance testing and optimisation

5.7. Fundamental Oxy-Fuel Combustion Research Carried Out within the ENCAP Project
Klas Anderson, Chalmers University

The fundamental studies on oxy-fuel combustion under the ENCAP project were presented. This includes combustion study undertaken in the 20 kW test rig of Stuttgart IVD and the 100 kW test rig of Chalmers University.

The objective of these combustion tests aims to establish combustion characteristic data for validation of CFD modelling and to support selection of flue gas treatment technology.

The coal combustion test includes characterisation of emission behaviour, ash quality, particle temperature under oxy-combustion mode as compared to air combustion mode. From this study, the results for the gas emission and temperature profiles for air fired vs 27% O_2 with recycled flue gas were shown. The effect of HNO injection and staging combustion on NOx emissions were also presented.

The oxy-natural gas combustion test includes characterisation of flame properties, gas concentrations, in-flame temperature measurements and radiation characteristics. From this study, the calculated emissivity for oxy-fuel combustion determined using a narrow angle radiometer was presented.

Finally, the presentation concludes with up-coming activities within the ENCAP experimental programme. This will involve the development of burner concept and design, investigation of radiation characteristics, burnout and emission behaviour and slagging, fouling test in a 100 kW and 500 kW combustion test rig.

5.8. Development in Oxy-Combustion Boiler: A View From Boiler Manufacturer
Timo Hyppänen, Foster Wheeler Oy

The point of view of the boiler manufacturer in the development for both oxy-combustion for PC and CFB boilers were presented.

The development in oxy-combustion for PC boilers is primarily aimed to establish optimum plant design and to maximise overall efficiency. This includes development and design of burners that will have stable ignition, safe operation and minimise NOx. The development in boilers is now focused on the determination of optimum location of burner and ports (secondary and tertiary comburent ports) and the design of internal radiant surfaces.

An update to the R&D effort in the development of oxy-CFB boiler development was presented. Advantages of CFB oxy-combustion were enumerated. Opportunities to significant size reduction and high boiler efficiency were stressed during the presentation. Some of the results from the bench test done in VTT (Technical Research Centre of Finland) showed the combustion profile of an Oxy-CFB in terms of their emissions and performance.

Finally, the presentation concluded by showing a roadmap of oxy-CFB development indicating the aim of demonstrating oxy-CFB power plant in the range of 20-50 MW_e range in the next 3 years and a 250 MW_e by 2015.

5.9. *Air Liquide's Air Separation Units: Mastering Design and Operations*
Guillaume de Souza, Air Liquide

The requirements for large air separation units for oxy-combustion pulverised coal boiler were noted. Air Liquide noted that currently oxygen production companies are capable of the following:

- Designing and operating very large ASU.
- Optimising ASU with significant energy savings
- Allow potential integration within the customer process
- Provide reliability and high availability

This presentation showcase that ASU could be designed and built based on customer requirements. This includes the possibility of providing an ASU which could be optimised depending on CAPEX and OPEX requirements and potential for process integration with high availability and reliability.

5.10. *Oxy-Combustion for CO2 Capture in Pulverised Coal Boilers*
Guillaume de Smedt, Air Liquide

Air Liquide presented their experience in the development of oxy-combustion technologies for various types of fuel. They have presented work on a 1.5 MW_{th} boiler simulator and demonstrated the safe and smooth conversion from air-fired to O_2/Flue Gas Recirculation operation.

Test result has achieved significant reduction in flue gas volume, an increase in CO_2 concentration from 15% to 80% (dry basis) with 5% air ingress. They noted an experience of NOx reduction by 60% - 70%. Test results showed that by controlling the amount of flue gas recirculation, heat transfer profile is not significantly affected thus it is not anticipated that there will be adverse side effect on boiler performance.

5.11. *Capturing CO_2 from Oxy-Fuel Combustion Flue Gas*
Minish Shah, Praxair

Considerations for CO_2 purity for use in EOR were discussed. Critical issues such as requirements for pipeline transport and reservoir safety were noted. The following were recommended as the preferred quality of the CO_2 for EOR application:

- Minimum recommended purity of 95%
- O_2 content should be less than 10 ppm
- H_2O is preferred to be reduced to a very low level – but to what extent will require further investigation.
- High level of impurities could potentially form a second phase therefore resulting to hammering

Results and assumptions used for their techno-economic study were presented. Factors affecting power consumption in CO_2 processing were noted and these include:

- Excess O_2 in combustion
- Air ingress
- O_2 purity
- CO_2 purity requirement

From the results of their study, the following conclusions were noted:

- Air ingress or leakage is a significant factor affecting power consumption; minimising air ingress will benefit oxy-combustion the most.
- Power savings in 95% O_2 vs 99.5% O_2 more than offsets extra power in CO2 purification
- Need to define CO2 purity requirement for sequestration
- Two stage flash provide slight advantage over one stage flash.

Research needs in CO_2 processing were identified:

- Purity specification for EOR and sequestration
  - Impact of impurities on pipeline materials
  - Impact of impurities on effectiveness of storage
  - Interaction with impurities from other capture sources
- Drying of CO_2 containing SO_2
- VLE of high pressure CO_2 containing flue gas impurities

5.12. Vattenfall Oxy-fuel Pilot Plant Study: Programme Overview

Uwe Burchardt, Vattenfall Europe Generation and Mining AG

The programme for their 30 MW_{th} pilot plant study was presented. The rationale behind the up-scaling study for burner and boiler development was explained.

This presentation briefly describes the following:

- Combustion test programme for both lignite and bituminous coal.
- Sources of air-ingress has been identified
- Operation procedure to be implemented. This consists of the start-up procedure with air-fired process, shift to oxy-combustion mode then to be followed by the assimilation of the CO_2 liquefaction process.
- Time schedule of the construction, commission and operation of the pilot plant

The primary aims of the oxyfuel pilot plant operation were discussed in detail:

- Test of the complete technology chain (C-input to CO_2 purity)
- Test the feasibility of oxy-combustion for lignite
- Practical test of the interaction of all components
- Determination of the actual CO_2 capture rate and attainable CO_2 purity.
- Testing for start-up and break down. Analysis of trouble cases
- Knowledge for officially demanding monitoring
- Experiences to the permission of a CO_2 free power station

5.13. Australian Japanese Cooperation on Oxy-Fuel Project for Plant Retrofit: Callide-A Project

Chris Spero, CS Energy

An update to the Japanese-Australian oxy-fuel combustion feasibility study and demonstration project was clearly spelled out in this presentation. This project consists of a feasibility study and test programme evaluating the viability of the oxy-firing technology. The demonstration plant feasibility study has a primary objective of assessing the technical and economic merit of oxy-fuel combustion for a plant retrofit.

The main deliverables for this feasibility study include application study based on 1000 MW plant simulation and the reference design for the Callide-A 30 MWe power plant.

The primary purpose of the test and evaluation is to provide data input to boiler model proposed by IHI and the optimisation of oxy-firing condition matching the heat transfer profile of the air fired case.

The current project involves the following tasks:

- Feasibility study under the CCSD R&D Programme which will include:
  - initial process design
  - assessment of primary design factors (coal reactivity, heat transfer properties, ash characterisation, and emissions)
  - process optimisation
  - preliminary design, layout and costing of ASU and product recovery train,
  - detailed design and costing of Callide-A retrofit boiler
  - preliminary assessment of CO_2 storage
  - large scale application study.

- Engineering design and funding
  - Reference design and EPC specification
  - EIS, risk review
  - Final costing
  - Contracts for construction
  - Incorporated Joint Venture Agreement
  - Agreements for funding, O&M and services

- Test and evaluation
  - Combustion behaviour of oxy-firing as compared to air-firing
    - Volatile matter yield and char reactivity
    - Coal ash properties
    - Boiler heat transfer characteristics and design parameters

The development programme and time schedule for this project was presented. The value proposition for this project was enumerated. Basically, this project aims to:

- Address to key knowledge gaps and issues relevant to oxy-firing in full scale boiler
- Provide a platform for commercialisation of oxy-fuel technology and a new technology benchmark
- Provide substantial IP benefit for future large scale plant design and project implementation experience

6. WORKSHOP DISCUSSION – THE HIGHLIGHTS

The workshop discussion was led by Dr. Sho Kobayashi of Praxair. Specifically, the discussion is based on the various points raised in the issue paper prepared by IEA Greenhouse Gas R&D Programme (See Appendix 3).

The discussion was focused on the following main topics:

- Various operation issues relevant to the recycled flue gas and its impact to the flame properties.

- Availability of basic technical information required in understanding the combustion characteristics of the oxy-coal combustion with recycled flue gas.

- The importance of establishing baseline information for the development of a reliable model that could be used as tools for design and analysis of the oxy-combustion flame.

- Understanding the mechanisms of pollutant emissions from an oxy-combustion flame which includes for NOx, SOx, particulate matters and mercury.

- Various operational issues involving plant safety, procedural routine for starting up, turn down and shut down, and dynamics involving the integration of operating the air separation unit, the power plant island and the CO_2 processing and compression train.

During the discussion, there are several points were highlighted. A few of these issues were noted below:

- The importance of ensuring high availability and reliability was clearly stressed during the discussion. Primarily, the goal of the Vattenfall's 30 MW pilot plant project and CSEnergy's Calide-A project is to establish a good understanding and learn the fundamental operation requirements of an oxy-coal combustion power plant to increase their confidence of having the desired reliability similar to current fleet of pulverised coal fired power plant.

- A discussion was on the potential benefits and possible failure of having an oxy-coal combustion boiler operating with minimal flue gas recirculation. It was noted that there could be a gain in terms of reduction in capital cost due to a more compact boiler however it was clearly stressed that this should be balanced against potential problems (ie. slagging) that may occur due to the higher temperature condition created by a higher oxygen concentration.

- An important point was raised with regard to regulations requirement with regard to the dispersion of the flue gas. It was clearly noted that due to lower volume and higher density of the flue gas, the dispersion radius could be smaller as compared to current PC boilers. This issue was raised during the discussion to highlight the importance of knowing the minimum stack height of an oxy-combustion boiler in case where emergency release of the flue gas is necessary.

- Another discussion was raised on the level of understanding toward processing and compression of CO_2 with high level of impurities. It was noted that there is still a significant gaps in knowledge with regard to the fundamental understanding of the phase diagram of CO_2 especially in the presence of other impurities.

7. NEXT STEPS

- The IEAGHG will place the copies of presentations and this meeting report on http://www.captureandstorage.info.

- The IEAGHG will continually monitor any new development in the R&D areas of Oxy-Combustion for power generation. This will not be limited to Oxy-Coal Combustion Technology.

8. LIST OF APPENDICES

Appendix 1: List of Attendees

Appendix 2: Workshop Presentations

Appendix 3: Issue Paper

Appendix 4: Other reference materials and contributed materials

This page is intentionally left blank

APPENDIX I

List of Delegates

1st International Oxy-Combustion Workshop
Cottbus, Germany
29th – 30th November 2005

Klas Andersson
Chalmers University
Göteborg, Sweden

Tel. No.: +46 31 772 1000
Fax No.: +46 31 772 3592
Email: klon@entek.chalmers.se

Marie Anheden
Vattenfall Utveckling AB
Stockholm, Sweden

Tel. No.: +46 8 739 62 12
Fax No.: +46 8 739 68 02
Email: marie.anheden@vattenfall.com

Ole Biede
Energi E2
Copenhagen, Denmark

Tel. No.: +45 4480 6447
Fax No.: +45 4480 6604
Email: obi@e2.dk

Luis Cañadas
Inerco SA
Seville, Spain

Tel. No.: +34 629 058 543
Fax No.: +34 954 461 329
Email: lcanadas@inerco.es

Eric Croiset
University of Waterloo
Canada

Tel. No.: +1 519 888 4567 x6472
Fax No.: +1 519 746 4979
Email: ecroiset@uwaterloo.ca

Guillaume De Smedt
Air Liquide
Jouy en Josas, France

Tel. No.: +33 1 39 07 62 89
Fax No.: +33 1 39 07 61 13
Email: guillaume.de-smedt@airliquide.com

Guillaume de Souza
Air Liquide
France

Tel. No.: +33 1 39 07 65 94
Fax No.:
Email: guillaume.desouza@airliquide.com

Hans Dekker
DCMR / VROM
Schiedam, The Netherlands

Tel. No.: +31 10 246 8286
Fax No.: +31 10 246 8283
Email: jsd@dcmr.nl

Mario Ditaranto
Sintef Energy Research
Trondheim, Norway

Tel. No.: +47 7359 3166
Fax No.: +47 7359 2889
Email: mario.ditaranto@sintef.no

Roger Dudill
Air Products
Crewe, Cheshire, United Kingdom

Tel. No.: +44 780 117 8571
Fax No.:
Email: dudillr@airproducts.com

Hans Eklund
Norsk Hydro ASA
Oslo, Norway

Tel. No.: +47 2253 8992
Fax No.:
Email: hans.ragnar.eklund@hydro.com

Reiner Feist
Vattenfall Europe Power Consult GmbH
Vetschau, Spreewald, Germany

Tel. No.: +49 35433 752419
Fax No.: +49 354433 2353
Email: reiner.feist@vattenfall.de

Udo Gade
Vattenfall Europe Power Consult GmbH
Vetschau, Spreewald, Germany

Tel. No.: +49 35433 752501
Fax No.: +49 354433 2353
Email: udo.gade@vattenfall.de

Ben Goh
E.On UK
Nottingham, United Kingdom

Tel. No.: +44 115 936 2451
Fax No.: +44 115 936 2205
Email: ben.goh@eon-uk.com

Scheffknecht Günter
University of Stuttgart
Stuttgart, Germany

Tel. No.: +49 711 685 8913
Fax No.: +49 711 685 3781
Email: guenter.scheffknecht@ivd.uni-stuttgart.de

Reinhardt Hassa
Vattenfall Europe Mining and Generation AG
Germany

Tel. No.:
Fax No.:
Email:

Klaus Hein
University of Stuttgart
Eutingen, Germany

Tel. No.: +49 7457 91690
Fax No.: +49 7457 91691
Email: klaus.r.g.hein@t-online.de

Arto Hotta
Foster Wheeler Energia Oy
Varkaus, Finland

Tel. No.: +358 10 393 7588
Fax No.: +358 10 393 7689
Email: arto.hotta@fwfin.fwc.com

Daniel Hultqvist
Vattenfall Europe Power Consult GmbH
Vetschau, Spreewald, Germany

Tel. No.: +49 35433 752419
Fax No.: +49 354433 2353
Email: daniel.hultqvist@vattenfall.de

Timo Hyppänen
Foster Wheeler Energia Oy
Varkaus, Finland

Tel. No.: +358 10 393 7587
Fax No.: +358 10 393 7689
Email: timo.hyppanen@fwfin.fwc.com

Mohamed Kanniche
EDF R&D
Chatou, France

Tel. No.: +33 1 30 87 70 93
Fax No.: +33 1 30 87 71 08
Email: mohamed.kanniche@edf.fr

Alfons Kather
Hamburg University of Technology
Hamburg, Germany

Tel. No.: +49 40 428 78 3043
Fax No.: +49 40 42 878 2467
Email: kather@tu-harburg.de

Mario Klemm
TU Dresden
Dresden, Germany

Tel. No.: +49 351 463 33471
Fax No.: +49 351 463 37753
Email: mklemm@metrs1.mw.tu-dresden.de

Frank Kluger
Alstom Power Boiler GmbH
Stuttgart, Germany

Tel. No.: +49 7 11917 1029
Fax No.: +49 7 11 917 1239
Email: frank.kluger@power.alstom.com

Sho Kobayashi
Praxair Inc.
Danbury , USA

Tel. No.: +1 203-837-2652
Fax No.: +1 203-837-2469
Email: sho_kobayashi@praxair.com

Henrik Kobro
Statoil
Stavanger, Norway

Tel. No.: +47 971 46 387
Fax No.: +47 5199 0050
Email: hkobro@statoil.com

Stein Koren
Gassnova
Porsgrunn, Norway

Tel. No.: +47 48195122
Fax No.: +47 35932201
Email: sk@gassnova.no

Axel Kranzmann
COORETEC
Germany

Tel. No.:
Fax No.:
Email: axel.kranzmann@bam.de

Etienne Lebas
IFP
Vernaison, France

Tel. No.: +33 4 78 02 25 14
Fax No.: +33 4 78 02 20 09
Email: etienne.lebas@ifp.fr

Göran Lindgren
Vattenfall Utveckling AB
Stockholm, Sweden

Tel. No.:
Fax No.:
Email: goran.lindgren@vattenfall.com

Mette Lindal Madsen
Energi E2
Copenhagen, Denmark

Tel. No.: +45 4480 6000
Fax No.: +45 4480 6604
Email: mlm@e2.dk

Jörg Maier
University of Stuttgart
Stuttgart, Germany

Tel. No.: +49 711 685 3396
Fax No.: +49 711 685 3491
Email: j.maier@ivd.uni-stuttgart.de

Keiji Makino
Ishikawajima-Harima Heavy Industry
Tokyo, Japan

Tel. No.: +81 3 3534 4302
Fax No.: +81 3 3534 4460
Email: keiji_makino@ihi.co.jp

Heike Meyer
Vattenfall Europe Power Consult GmbH
Vetschau, Spreewald, Germany

Tel. No.: +49 35433 752437
Fax No.: +49 354433 2353
Email: heike.meyer@vattenfall.de

Stuart Mitchell
Mitsui Babcock Energy Ltd.
Renfrew, United Kingdom

Tel. No.: +44 141 885 3953
Fax No.: +44 141 885 3860
Email: smitchell@mitsuibabcock.com

Miguel Morales
Inerco SA
Seville, Spain

Tel. No.: +34 606 384 104
Fax No.: +34 954 461 329
Email: mmorales@inerco.es

Dong-Soon Noh
Korea Institute of Energy Research
Daejeon, South Korea

Tel. No.: +82 42 860 3347
Fax No.: +82 42 860 3102
Email: dsnoh@kier.re.kr

Per Ottosen
Energi E2
Copenhagen, Denmark

Tel. No.: +45 4480 6000
Fax No.: +45 4480 6604
Email: pot@e2.dk

Miro Podhorsky
Balcke-Dürr GmBH
Ratingen, Germany

Tel. No.: +49 2102 1669 596
Fax No.: +49 2102 1669 617
Email: miroslav.podhorsky@cts.spx.com

Keith Pronske
Clean Energy Systems Inc.
USA

Tel. No.: +1 916 379 9143
Fax No.: +1 916 379 9146
Email: klpronske@cleanenergysystems.com

Detlef Radunsky
Vattenfall Europe Power Consult GmbH
Vetschau, Spreewald, Germany

Tel. No.: +49 35433 752552
Fax No.: +49 354433 2353
Email: detlef.radunsky@vattenfall.de

Anand Rao
Carnegie Mellon University
Pittsburgh, PA, USA

Tel. No.: +1 412 268 5489
Fax No.: +1 412 268 3757
Email: abr@cmu.edu

Nicola Rossi
ENEL SpA
Pisa, Italy

Tel. No.: +39 050 6185686
Fax No.:
Email: nicola.rossi@enel.it

Stanley Santos
IEA Greenhouse Gas R&D Programme
Cheltenham, United Kingdom

Tel. No.: +44 1242 680753
Fax No.: +44 1242 680758
Email: stanley@ieagreen.org

Frank Schwendig
RWE Power AG
Essen, Germany

Tel. No.: +49 201 12 41376
Fax No.: +49 201 12 27408
Email: frank.schwendig@rwe.com

Minish Shah
Praxair Inc.
Tonawanda, NY, USA

Tel. No.: +1 716 879 2623
Fax No.: +1 716 879 7931
Email: minish_shah@praxair.com

William Simmons
Coaltek LLC / Jupiter Oxygen Corp.
Evansville, Indiana, USA

Tel. No.: +1 812 402 2211
Fax No.: +1 812 402 2212
Email: wsimmons@coalteck.com

Chris Spero
CSEnergy
Queenslands, Australia

Tel. No.:
Fax No.:
Email: cspero@csenergy.com.au

Fred Starr
Institute of Energy - EC/JRC
Petten, The Netherlands

Tel. No.: +31 224 565 085
Fax No.: +31 224 565 623
Email: frederick.starr@jrc.nl

Bob Stobbs
Canadian Clean Power Coalition
Regina, Sk., Canada

Tel. No.: +1 306 566 3326
Fax No.: +1 306 566 3348
Email: bstobbs@saskpower.com

Lars Stromberg
Vattenfall AB
Stockholm, Sweden

Tel. No.: +46 8 739 55 11
Fax No.: +46 8 739 50 48
Email: lars.stromberg@vattenfall.com

Nick ten Asbroek
TNO
Apeldoorn, The Netherlands

Tel. No.: +31 555493370
Fax No.: +31 555493410
Email: nick.tenasbroek@tno.nl

Metz Thomas
Siemens
Erlangen, Germany

Tel. No.: +49 9131 18 5069
Fax No.: +49 9131 18 7403
Email: thomas.metz@siemens.com

Henrik Thuman
Chalmers University
Göteborg, Sweden

Tel. No.: +46 31 772 1000
Fax No.: +46 31 772 3592
Email: henrik.thuman@chalmers.se

John Topper
IEA Greenhouse Gas R&D Programme
Cheltenham, United Kingdom

Tel. No.: +44 1242 680753
Fax No.: +44 1242 680758
Email: john.topper@iea-coal.org.uk

Vince White
Air Products plc
Walton on Thames, United Kingdom

Tel. No.: +44 1932 249948
Fax No.: +44 1932 258135
Email: whitev@airproducts.com

Jen Wolf
Vattenfall Utveckling AB
Stockholm, Sweden

Tel. No.:
Fax No.:
Email: jens.wolf@vattenfall.com

Yinying Yan
Vattenfall Utveckling AB
Stockholm, Sweden

Tel. No.:
Fax No.:
Email: jinying.yan@vattenfall.com

Terry Wall
University of Newcastle
New South Wales, Australia

Tel. No.: +61 2 49 216179
Fax No.: +61 2 49 21 6920
Email: terry.wall@newcastle.edu.au

Dieter Winkler
Alstom (Switzerland)
Baden, Switzerland

Tel. No.: +41 56 486 7003
Fax No.: +41 56 486 7389
Email: dieter.winkler@power.altsom.com

Toshihiko Yamada
Ishikawajima-Harima Heavy Industry
Tokyo, Japan

Tel. No.: +81 3 3534 4381
Fax No.: +81 3 3534 4460
Email: toshihiko_yamada@ihi.co.jp

Kourosh Zanganeh
CANMET
Nepean, Ontario, Canada

Tel. No.:
Fax No.:
Email: kzangane@nrcan.gc.ca

This page is intentionally left blank

APPENDIX 2

LIST OF PRESENTATIONS

- Welcome Address – Vattenfall AB
  Welcome Address - Vattenfall Europe Mining & Generation: The Backbone of the Energy Group
  Reinhardt Hassa, Member of the Mgmt. Board, Vattenfall Europe Mining and Generation AG

- Welcome Address – IEA Greenhouse Gas R&D Programme
  IEA Greenhouse Gas R&D Programme: Background and Introduction to Oxy-Coal Network
  John Topper, Managing Director, IEA Environmental Project Ltd.

- Keynote Presentation
  Overview of the Oxy-Fuel Combustion Studies in Japan
  Keiji Makino, Chief Executive Engineer, IHI, Japan

- Presentation 01
  Oxy-Fuel Combustion for Coal Fired Power Plant: What is the Current State of Knowledge
  Stanley Santos, IEA Greenhouse Gas R&D Programme, UK

- Presentation 02
  Fundamentals of Oxy-Fuel Combustion
  Prof. Terry Wall, University of Newcastle, Australia

- Presentation 03
  Technology Choice and Benchmarking Studies
  Prof. Lars Strömberg, Vattenfall AB, Sweden

- Presentation 04
  Vattenfall's Activities on Oxy-Fuel Combustion Studies
  Prof. Lars Strömberg, Vattenfall AB, Sweden

- Presentation 05
  An Overview of Oxy-Fuel Combustion R&D Programme in CANMET
  Kourosh Zanganeh, CANMET, Canada

- Presentation 06
  Fundamental Oxy-Fuel Combustion Research Carried Out within the ENCAP Project
  Klas Anderson, Chalmers University, Sweden

- Presentation 07
  Development in Oxy-Coal Combustion Boiler: A View from Boiler Manufacturer
  Timo Hyppänen, Foster Wheeler Oy, Finland

- Presentation 08
  Air Liquide Air Separation Units – Mastering Design and Operations
  Guillaume de Souza, Air Liquide, France

- Presentation 09
  Oxy-Combustion for CO_2 Capture in Pulverized Coal Boilers
  Guillaume de Smedt and Guillaume de Souza, Air Liquide, France

- Presentation 10
  Capturing CO_2 from Oxy-Fuel Combustion Flue Gas
  Minish Shah, Praxair, USA

- Presentation 11
  Vattenfall Oxy-fuel Pilot Plant Study – Programme Overview
  Uwe Burchardt, Vattenfall Europe Generation and Mining, Germany

- Presentation 12
  Australian Japanese Co-operation on OxyFuel Pilot Project for Plant Retrofit – Callide-A Project
  Chris Spero, CSEnergy, Australia

This page is intentionally left blank

Inaugural Workshop

International Oxy-Combustion Research Network

Vattenfall Europe Mining and Generation AG Head Office
Cottbus, Germany

29th and 30th November 2005

WELCOME ADDRESS

Vattenfall Europe Mining & Generation
The Backbone of the Energy Group

by:

Reinhardt Hassa
Member of the Mgmt. Board, Vattenfall Europe Mining & Generation AG

This page is intentionally left blank

VATTENFALL EUROPE

Vattenfall Europe Mining & Generation
The backbone of the energy group

Reinhardt Hassa

VATTENFALL

VATTENFALL EUROPE

At a Glance

Lignite mining	59,0 Mio. t
Power generation (gross)	70,5 TWh
Sales	
Refining products	1,3 Mio.t
Drinking water	4,5 Mio. m³
Process water	29,8 Mio. m³

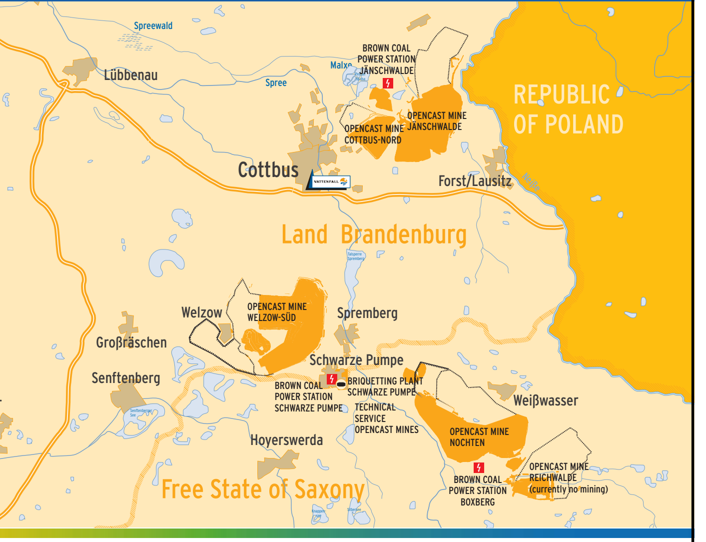
As of: 12/2004

2

VATTENFALL

VATTENFALL EUROPE

Locations in Lusatia



3

VATTENFALL

VATTENFALL EUROPE

Highly-Efficient Coal Mining

Run-of-mine coal extraction in 2004
for each open-cast mine

Jänschwalde open-cast mine	14.83 million t
Cottbus-Nord open-cast mine	5.48 million t
Welzow-Süd open-cast mine	20.65 million t
Nochten open-cast mine	17.68 million t
Total	**59 million t**

4

VATTENFALL

VATTENFALL EUROPE

Power Plant Park I

Base load		
4 lignite-fired power plants	7.420	MW
3 nuclear power station shares	1.470	MW
Medium load		
1 hard coal-fired power plant	553	MW
Peak load		
10 water power plants	2.902	MW
5 gas turbine power plants	968	MW
Total	**13.313**	**MW**

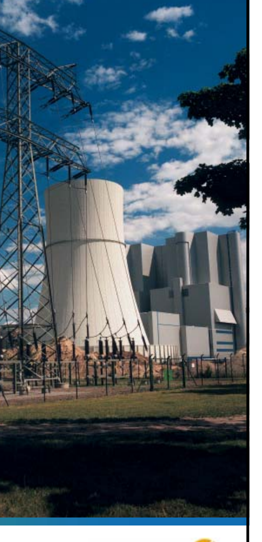
5

VATTENFALL

VATTENFALL EUROPE

Power Plant Park II

Lignite		
Jänschwalde	3.000	MW
Boxberg	1.900	MW
Schwarze Pumpe	1.600	MW
Lippendorf	920	MW
Hard coal		
Rostock	553	MW
Total	**7.973**	**MW**



6

VATTENFALL

VATTENFALL EUROPE

Prospects by Mining & Generation - Investment projects

Short- and middle-term projects:

New building of wind power station and biomass CHP

Co-burning of derived fuels in all lignite power plants

Long-term projects:

Improvement of the lignite railway-transportation

Re-opening of the open-cast mine Reichwalde with an yearly operating capacity of 10 mio.t

New building of a 670-MW-unit based on lignite in Boxberg

New building of a hard coal power plant in Moorburg (1640 MW, 450 MW_{th})

7

VATTENFALL

VATTENFALL EUROPE

Computersimulation of the 670 MW- lignite power plant in Boxberg

8

VATTENFALL

VATTENFALL EUROPE

Computersimulation of the 2x820 MW- hard coal power plant in Moorburg

9

VATTENFALL

VATTENFALL EUROPE

Environmental Protection

- Environmental protection is one of our core competencies.
- Since the beginning of the nineties, a 10 billion Euro investment programme has been realised.
- Out of date power plants were shut down or modernised.
- Lignite-based power plants with the world-wide highest efficiencies and most up-to-date environmental technology have been newly built.
- The existing power plant park and its technical components were and are further developed consistently.
- The main focus of our involvement in the environment is the responsibility of recultivating the landscape after mining has taken place.

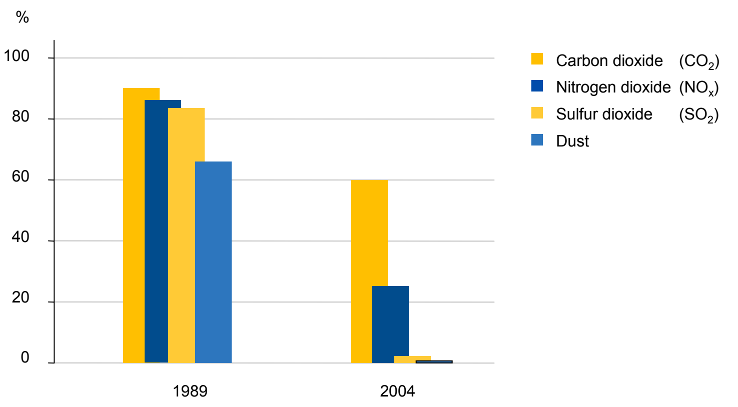
10

VATTENFALL

VATTENFALL EUROPE

Development of Emission

Reference Year 1989



11

VATTENFALL

VATTENFALL EUROPE

The Oxyfuel technology

Why Oxyfuel ?

Power station process with high efficiency - potential

Highest CO_2 - capture potential

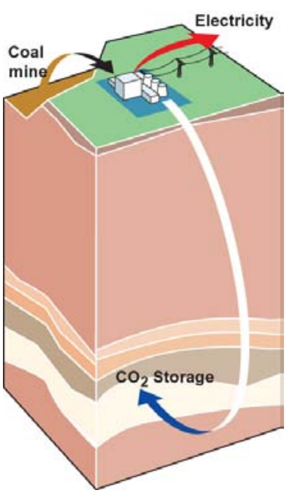
Good pre-estimation of operation and investment costs possible

Steps toward the Oxyfuel plant

2008 Pilot plant 30 MW_{th}

2015 Demo plant 300 – 600 MW_{th}

2020 Commercial power plant >1000 MW_{th}



12

VATTENFALL


VATTENFALL EUROPE
Vattenfall Europe Mining & Generation
The backbone of the energy group
Thanks for your attention
VATTENFALL

This page is intentionally left blank

Inaugural Workshop

International Oxy-Combustion Research Network

Vattenfall Europe Mining and Generation AG Head Office
Cottbus, Germany

29th and 30th November 2005

WELCOME ADDRESS

IEA Greenhouse Gas R&D Programme
Background & Introduction to Oxy-Combustion Network

by:

John Topper
Managing Director, IEA Environmental Project Ltd.

This page is intentionally left blank

The IEA Greenhouse Gas R&D Programme

Background and
Introduction to Oxy-Combustion Network

November 2005

IEA Greenhouse Gas R&D Programme

- A collaborative research programme which started in 1991.
- Its main role is to evaluate technologies that can reduce greenhouse gas emissions.
- Aim is to:

Provide our members with informed information on the role that technology can play in reducing greenhouse gas emissions

IEA Greenhouse Gas R&D Programme

Programme Members

ALSTOM bp Chevron EniTecnologie EPRI
ExxonMobil REPSOL YPF RWE TOTAL

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

Membership Situation

- Membership expanding rapidly
- GERMANY applied and approved by Executive
- OPEC in advanced stage of negotiation
- New Sponsors – approved by Executive and awaiting IEA confirmation

BG GROUP e·on STATOIL VATTENFALL

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

Previous Phases

- The Agreement has been operating for 13 years. It has:
  - Accumulated >100 studies covering carbon capture and storage (CCS), other mitigation technologies, and alternative energy carriers.
  - Succeeded in establishing CCS as a mitigation option capable of major reductions in the emission of CO_2 to atmosphere.

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

Phase 4

- Finished Nov. 2004. During phase 4:
  - CCS moved, from being a technical possibility, firmly onto policymakers' agendas.
  - Activities expanded to include: research facilitation, research networks, and communications initiatives. All aimed at confirming CCS as a major option for climate change mitigation.

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

Phase 5

- New phase (5) started at end of 2004:
- Flexible & Responsive: Members debate and decide details at each ExCo.
- Strategic themes:
  - Generating technology and market Information on CCS and related options.
  - Confidence-building in mitigation technology This workshop!
  - Dissemination of information about CCS and related options

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

Recent Technical Studies

Approximately 100 studies – list available

- In the last year, member's studies, included:
  - Post combustion capture of CO_2 from power generation
  - Oxycombustion for power generation and CO_2 capture
  - Cost and capacity for CO_2 storage in Europe and N America
  - Monitoring requirements for CCS
  - Long term framework for CCS
  - Modelling ocean storage of CO_2
  - Use of CDM for CCS
  - Carbon sequestration in soils

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

Confidence Building

- Initiate and organise international research networks e.g.
  - Solvent capture
  - Biofixation - algae
  - Monitoring underground storage
  - Well bore Integrity
  - NEW – Risk Assessment
  - NEW – Oxyfuel
- Details at www.co2captureandstorage.info

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

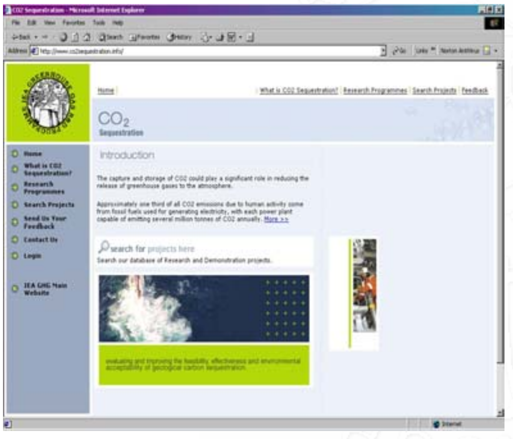
www.ieagreen.org.uk

- Provides information on Programmes Activities
- List of technical reports, papers and presentations
- Links to GHGT Conference web sites
- Open and Members only sites

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

www.co2captureandstorage.info



- Aimed to provide information source on CCS.
- Contains database of practical R,D&D projects.
- Hosts risk scenarios data base
- Provides network information
- NEW – CO_2 Emission sources database

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

GHGT8

19th-22nd June 2006, Trondheim, Norway

To be preceded by 9th International CO2 Capture Network in Copenhagen on 16 June

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

The Oxy Fuel Network

Representation at this 1st meeting

- 65 registrants from 16 countries, about twice what we guessed.
- Australia, Canada, Denmark, Finland, France, Germany, Italy, Japan, Korea, Netherlands, Norway, Spain, Sweden, Switzerland, UK, USA
- And we were turning people away 2 weeks before the event as we have run out of space

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

The Oxy Fuel Network

- Will it fill a gap ?
- How often should it meet?
- Should it concentrate on single or multithemes?
- Where will it meet – Volunteers for next event welcome – especially from non-EU locations
- Stanley Santos is the GHG co-ordinator. Please talk to him – he needs your feed-back
- Stanley will briefly run through the Agenda

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

Overview to the Meeting

- Role of IEA Greenhouse Gas R&D Programme
  - Organise this Network to provide a forum for discussion on the issues regarding Oxy-Fuel Combustion as a Carbon Capture Technology option – and to promote co-operative action.
- Theme for the Inaugural Workshop:
  - **"Oxy-Combustion Application for a Coal Fired Power Plant"**
- We need feedback from our participants to determine the key research priorities.
- Through discussion and reply to survey

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

AGENDA

- Session 1:
  - Technology Benchmarking and Modelling Studies – Review of OxyFuel Combustion R&D Activities
  - Chaired by John Topper, IEAGHG, UK
- Plant Visit to the Schwarze Pumpe Power Station
  - Overview to the Vattenfall 30MW Pilot Plant Studies
- Session 2:
  - Development in Oxy-Fuel Combustion Studies – Work in Progress
  - Chaired by Prof. Klaus Hein, University of Stuttgart, Germany
- Session 3:
  - O_2 Production and CO_2 Processing – an overview to the R&D Activities for Power Generation Industry Application
  - Chaired by Roger Dudill, Air Products, UK
- Session 4:
  - An Overview, Progress and Development in Large Scale Oxy-Fuel Combustion Pilot Plant Studies
  - Chaired by Sho Kobayashi, Praxair, USA
- Discussion Forum

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

Administrative Announcement

- Information Package
- Plant Visit and Afternoon Session
- Bus Arrangement
- Dinner Arrangement
- Safety Announcement

www.ieagreen.org.uk

This page is intentionally left blank

Inaugural Workshop

International Oxy-Combustion Research Network

Vattenfall Europe Mining and Generation AG Head Office
Cottbus, Germany

29th and 30th November 2005

KEYNOTE PRESENTATION

Overview of the Oxy-Fuel Combustion Studies in Japan

by:

Prof. Keiji Makino
Chief Executive Engineer, IHI

This page is intentionally left blank

IHI

IEA Greenhouse Gas R&D Programme

Oxy-Fuel Combustion Research Network

Overview of Oxy-Fuel Combustion Studies in Japan

Keiji MAKINO

Executive Chief Engineer

Ishikawajima-Harima Heavy Industries Co., Ltd.

Tokyo, JAPAN

Contents

IHI

1. Japanese Strategy for CO_2 Reduction
2. Oxy-firing Studies in Japan
3. Study of 1000MW Oxy-firing Super-Critical Unit
4. Japan-Australia Oxy-firing Project
5. Conclusion

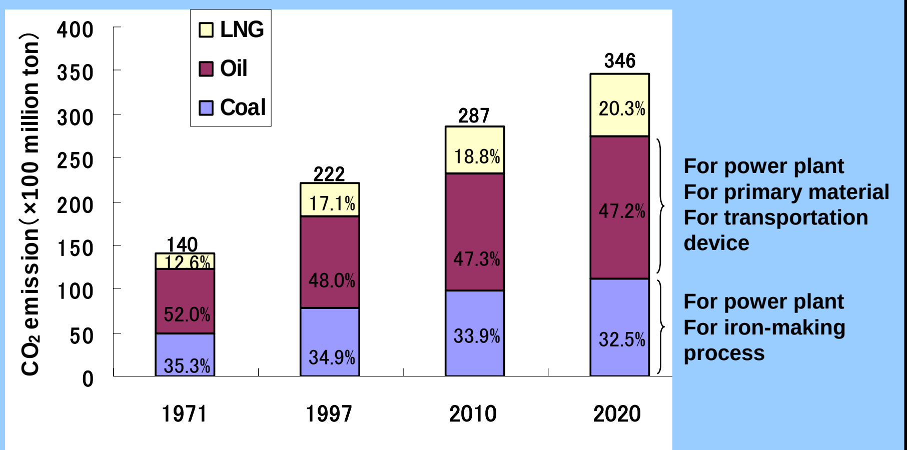
Contents

IHI

1. **Japanese Strategy for CO_2 Reduction**
2. Oxy-firing Studies in Japan
3. Study of 1000MW Oxy-firing Super-Critical Unit
4. Japan-Australia Oxy-firing Project
5. Conclusion

Trend of World CO_2 Emission

IHI



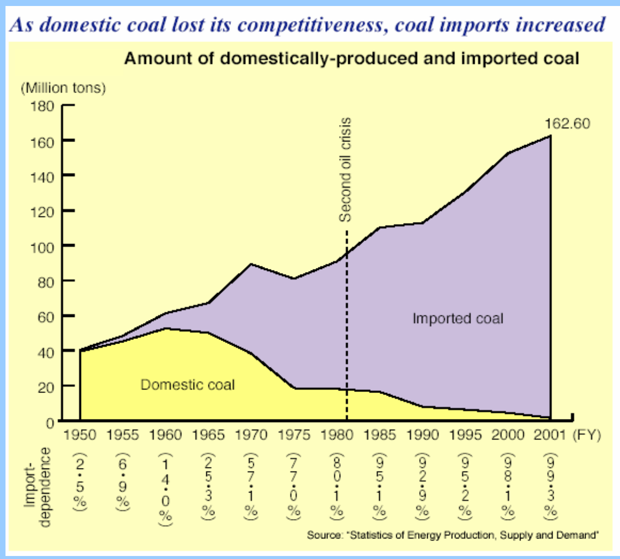
CO_2 emission in the world

<u>CO_2 reduction is prime task for global warming and is not depend on the place to recover CO_2.</u>

※By IEA/World Energy Outlook 2000

Japanese Coal Import

IHI

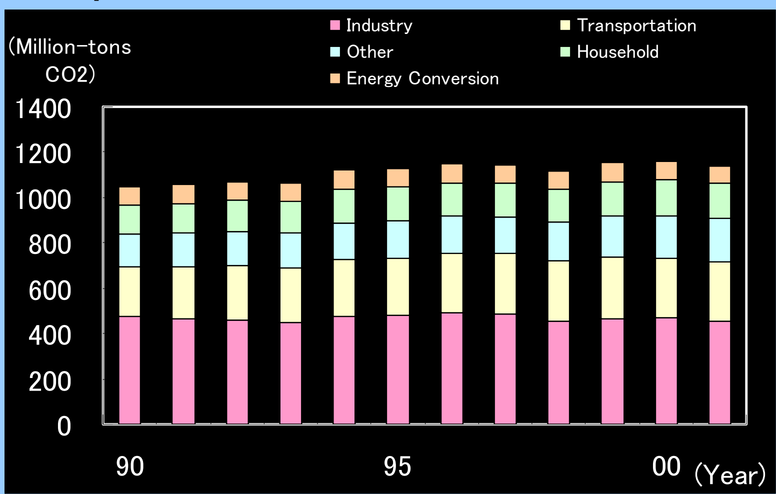


From METI Home Page

KYOTO Protocol

IHI

Japan must reduce GHG at –6%



CO_2 Emission in Japan

From METI Home Page

Use of Coal

IHI

Use of Coal = OK ?

If coal is as clean as other fuels,
situation of coal will change dramatically.

↓

Technological Innovation

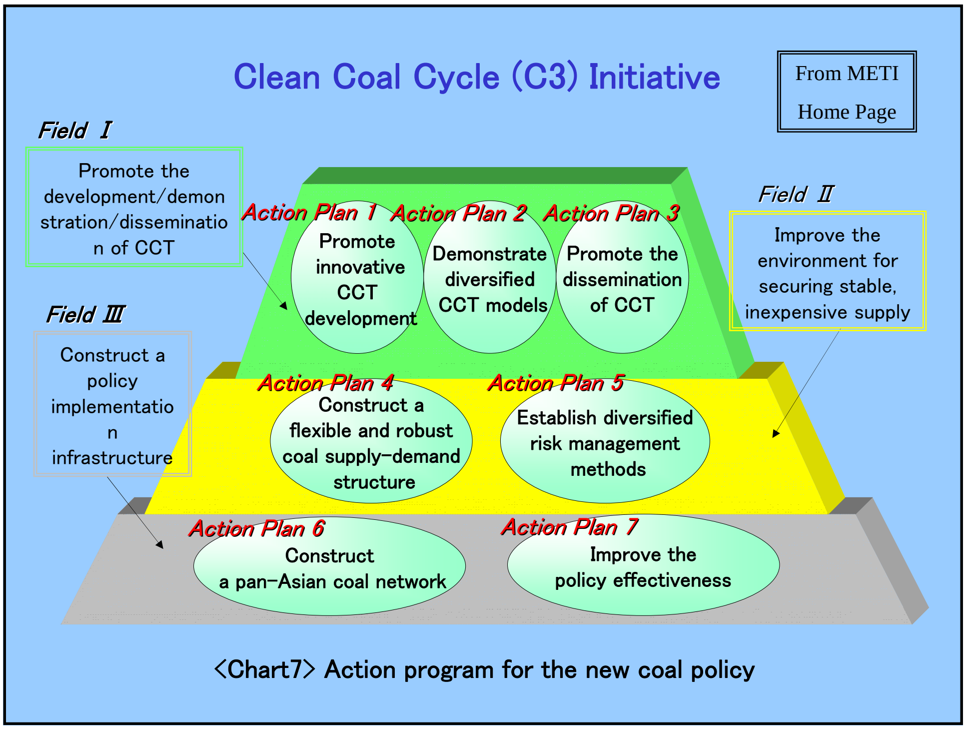
New Coal Policy in Japan

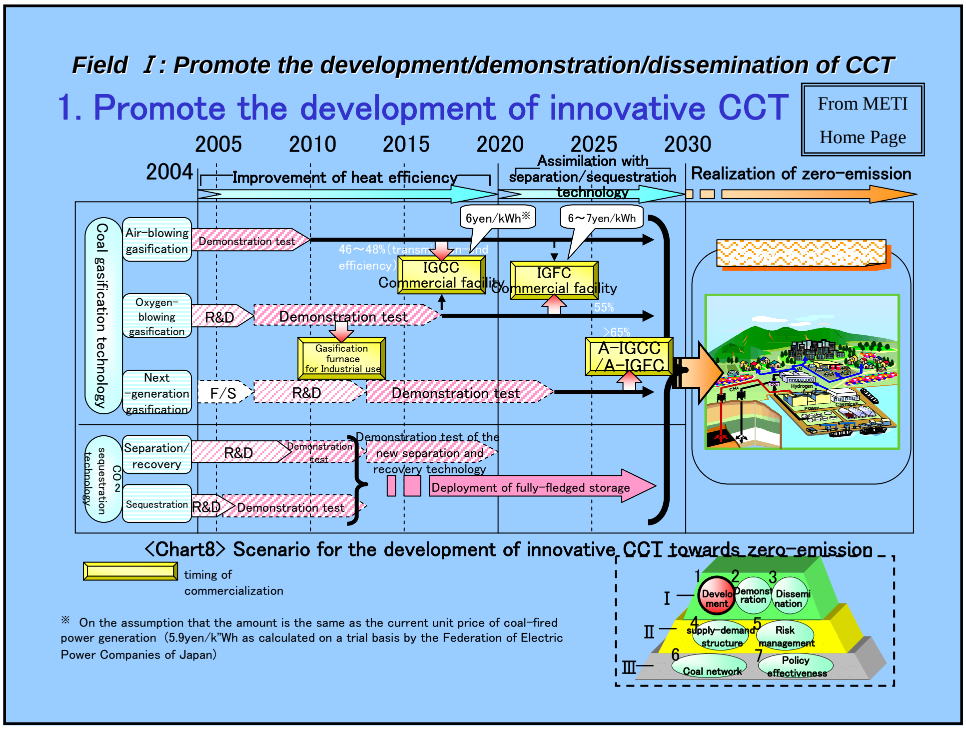
IHI

Japan's new coal policy towards 2030 called

"Clean Coal Cycle (C3) Initiative"

is presented and launched. To promote the development of innovative CCT towards the realization of zero-emission utilization is described in C3 Initiative.


Clean Coal Cycle (C3) Initiative
From METI Home Page
Field Ⅰ
Promote the development/demonstration/dissemination of CCT
Field Ⅱ
Improve the environment for securing stable, inexpensive supply
Field Ⅲ
Construct a policy implementation infrastructure
Action Plan 1
Promote innovative CCT development
Action Plan 2
Demonstrate diversified CCT models
Action Plan 3
Promote the dissemination of CCT
Action Plan 4
Construct a flexible and robust coal supply-demand structure
Action Plan 5
Establish diversified risk management methods
Action Plan 6
Construct a pan-Asian coal network
Action Plan 7
Improve the policy effectiveness
<Chart7> Action program for the new coal policy


Field Ⅰ: Promote the development/demonstration/dissemination of CCT
1. Promote the development of innovative CCT
From METI Home Page
2004
2005
2010
2015
2020
2025
2030
Improvement of heat efficiency
Assimilation with separation/sequestration technology
Realization of zero-emission
Coal gasification technology
Air-blowing gasification
Oxygen-blowing gasification
Next-generation gasification
Demonstration test
6yen/kWh※
6～7yen/kWh
IGCC Commercial facility
IGFC Commercial facility
R&D
Demonstration test
Gasification furnace for Industrial use
A-IGCC /A-IGFC
F/S
R&D
Demonstration test
CO2 sequestration technology
Separation/recovery
Sequestration
R&D
Demonstration test
Demonstration test of the new separation and recovery technology
Deployment of fully-fledged storage
<Chart8> Scenario for the development of innovative CCT towards zero-emission
timing of commercialization
※ On the assumption that the amount is the same as the current unit price of coal-fired power generation (5.9yen/kWh as calculated on a trial basis by the Federation of Electric Power Companies of Japan)
Development
Demonstration
Dissemination
supply-demand structure
Risk management
Coal network
Policy effectiveness

Field Ⅰ　　CCT

IHI

1. Promote the development of innovative CCT

*F/S of Advanced Gasification

*Oxy-fuel to existing boiler with Australia

*IGCC, IGFC, HyPr-RING

2. Demonstrate diversified CCT models

*F/S of co-production with gasification

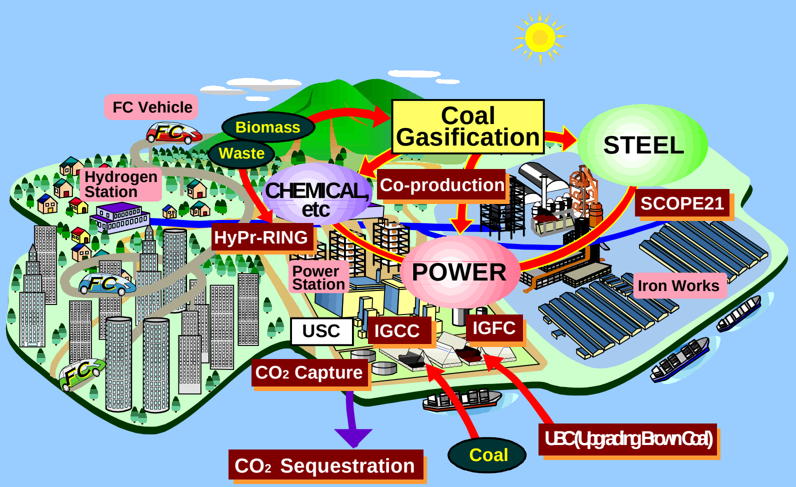
*F/S of CTL/H_2 from coal/biomass/plastics gasification

Three Study perspectives (2)

From METI Home Page

– Medium– to long–term perspective towards 2030

CCT Spreading Energy Sector in Japan(2030)



Contents

IHI

1. Japanese Strategy for CO_2 Reduction
2. Oxy-firing Studies in Japan
3. Study of 1000MW Oxy-firing Super-Critical Unit
4. Japan-Australia Oxy-firing Project
5. Conclusion

2. Oxy-firing Studies in Japan

IHI

- Ignition and Flame Propagation
- Fundamental Test of Oxy–firing (at TIT)
- In-furnace Desulfurization of Oxy–firing (at TIT)
- Combustion Test and CO_2 Compression Demo–Test

CO_2 Reduction Technology from Coal Fired Power Plant

IHI

○Newly-installed plant

- High efficiency
  - IGCC
  - 700℃ class USC

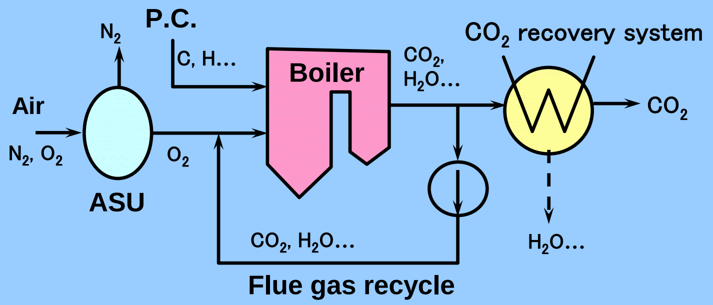
○Existing plant

- High efficiency
- Switching fuel
- Positive CO_2 recovery
  - Oxy-firing
  - Chemical absorption

Oxy-fuel Combustion System

IHI

Concept



Characteristics

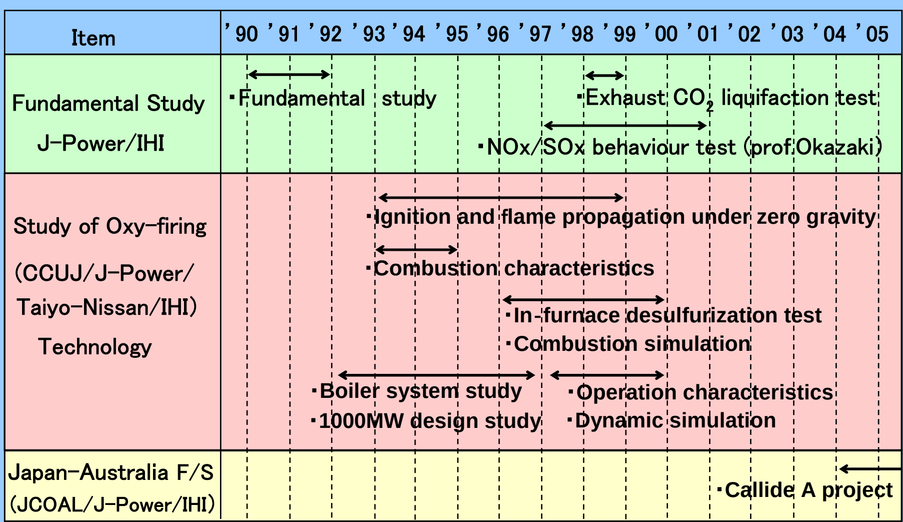
- Direct flue gas (CO_2) recover
- Compactification or unnecessity of flue gas treatment equipment
- Lower NOx and SO_2 emission
- Higher plant efficiency is expected for CO_2 recover

Coal Combustion under CO_2 Atmosphere

Item		Combustion with air	Combustion with oxygen
Windbox	O2	21%	21～30%
	N2	79%	(0)～10%
	CO2	0%	40～50%
	H2O	Small	10～20%
	Others	—	NOx、SO2・・・
Flue gas	O2	3～4%	3～4%
	N2	70～75%	(0)～10%
	CO2	12～14%	60～70%
	H2O	10～15%	20～25%
	Others	NOx、SO2・・・	NOx、SO2・・・

(Wet % base)

Calendar of Japanese Oxy-firing Study



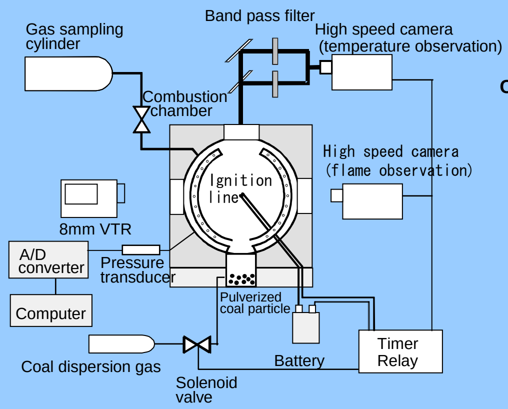
Ignition Characteristics

IHI

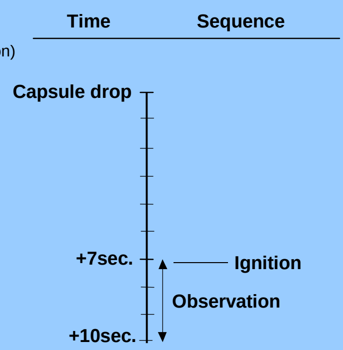
Small gravity test

Device : Free drop chamber

Gravity : 1.0×10^{-4}g、10seconds



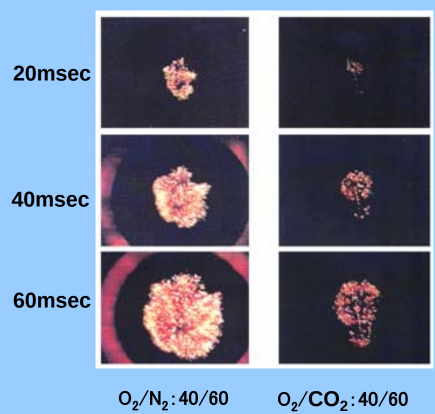
Device

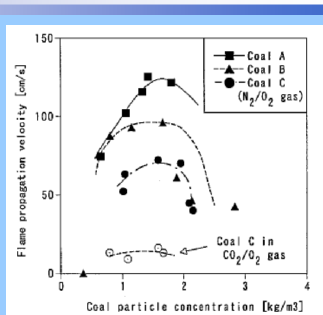


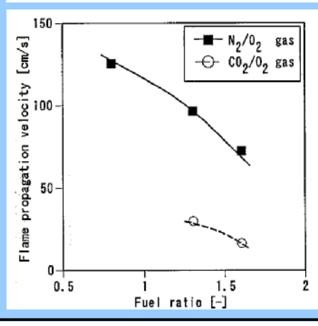
Test procedure

Ignition Characteristics

IHI

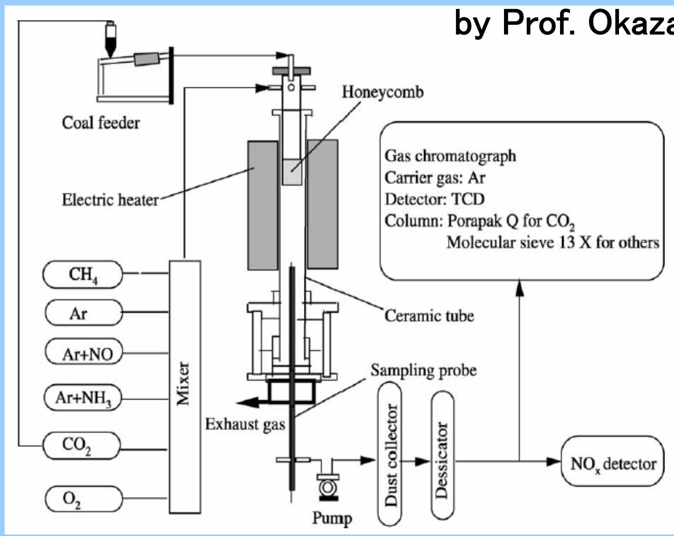






NOx Reduction Test

by Prof. Okazaki



Experimental system to simulate O2/CO2 coal combustion

School of Engineering *Tokyo Institute of Technology*

From Prof. Okazaki

Drastic NOx Reduction

(NOx: mainly due to Fuel-NOx)

(Drastic decrease of Conversion Ratio from Fuel-N to NOx)

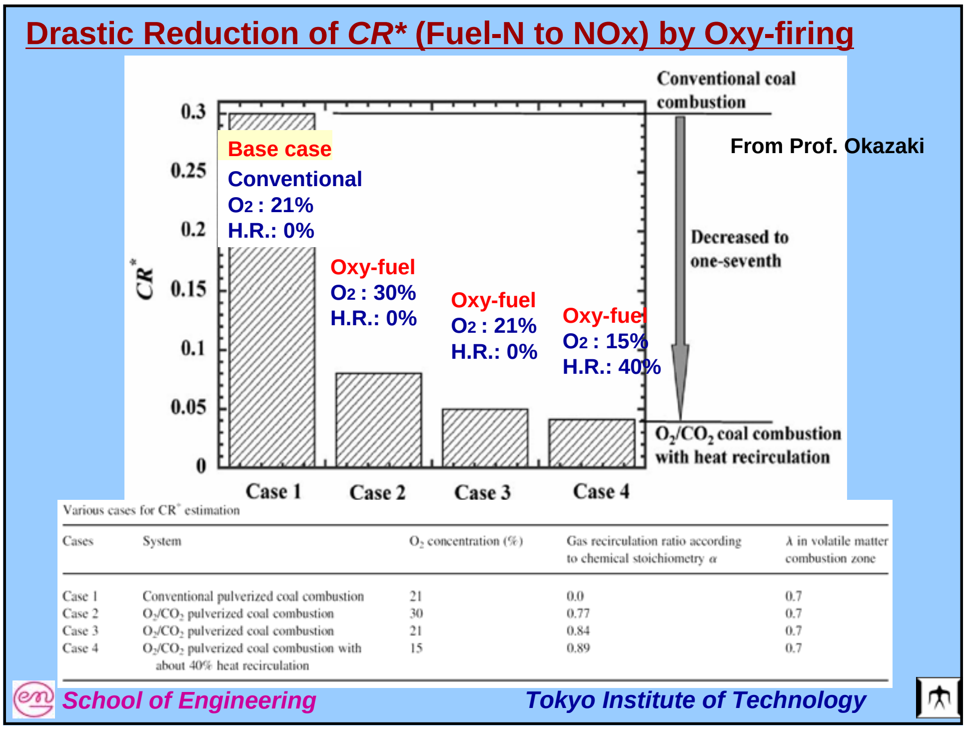
Summary of CR^* values for O_2/CO_2 coal combustion

λ (oxygen-fuel stoichiometric ratio)	0.7	1.0	1.2
NO concentration in exhaust gas	1130 ppm	1710 ppm	1490 ppm
CR^*	0.05	0.12	0.13
Ratio of CR^* to that of air combustion	17 % (1/6)	25 % (1/4)	26 % (1/4)

CR^*: conversion ratio from fuel-N to exhausted NO

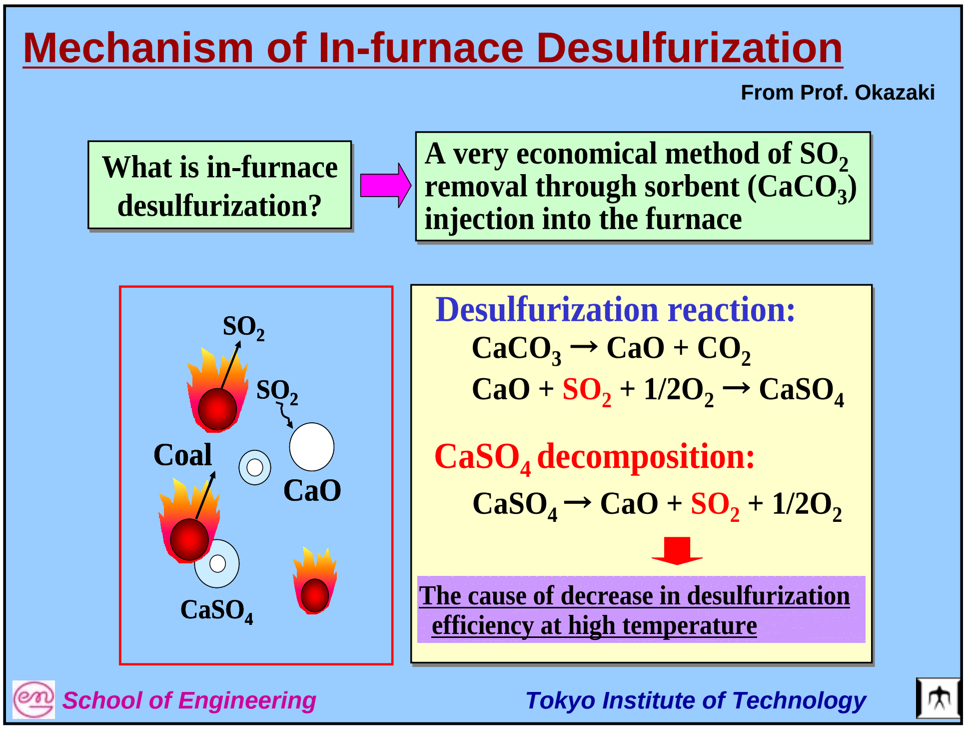
Ratio of CR^* to that of air combustion $= \dfrac{CR^* \text{ in } O_2/CO_2 \text{ coal combustion}}{CR^* \text{ in conventional coal combustion in air}}$

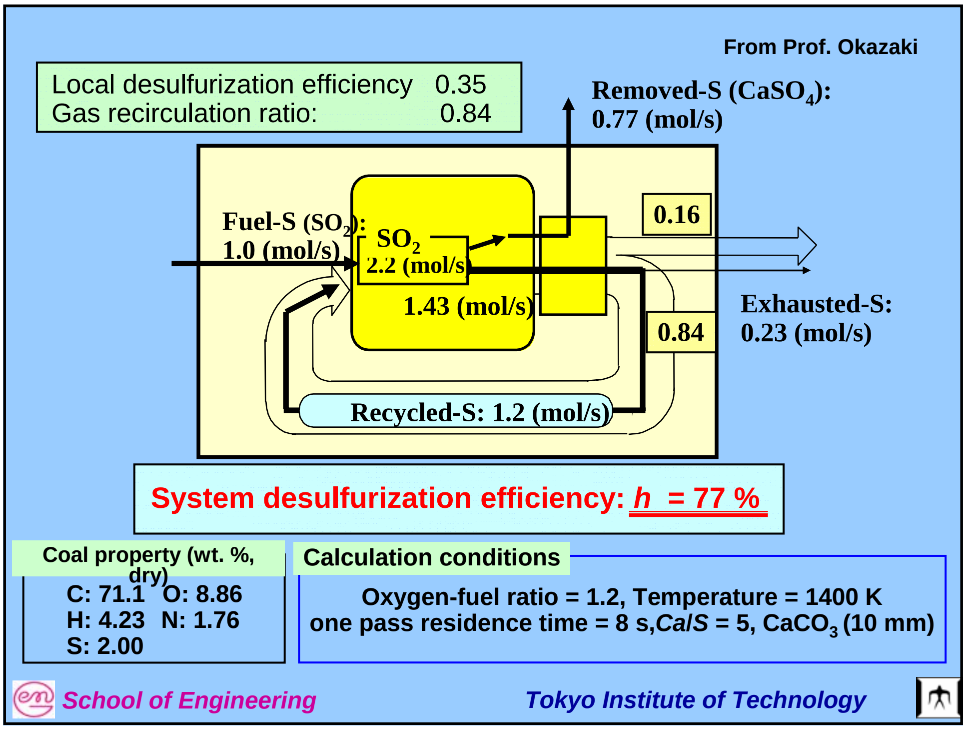
School of Engineering *Tokyo Institute of Technology*

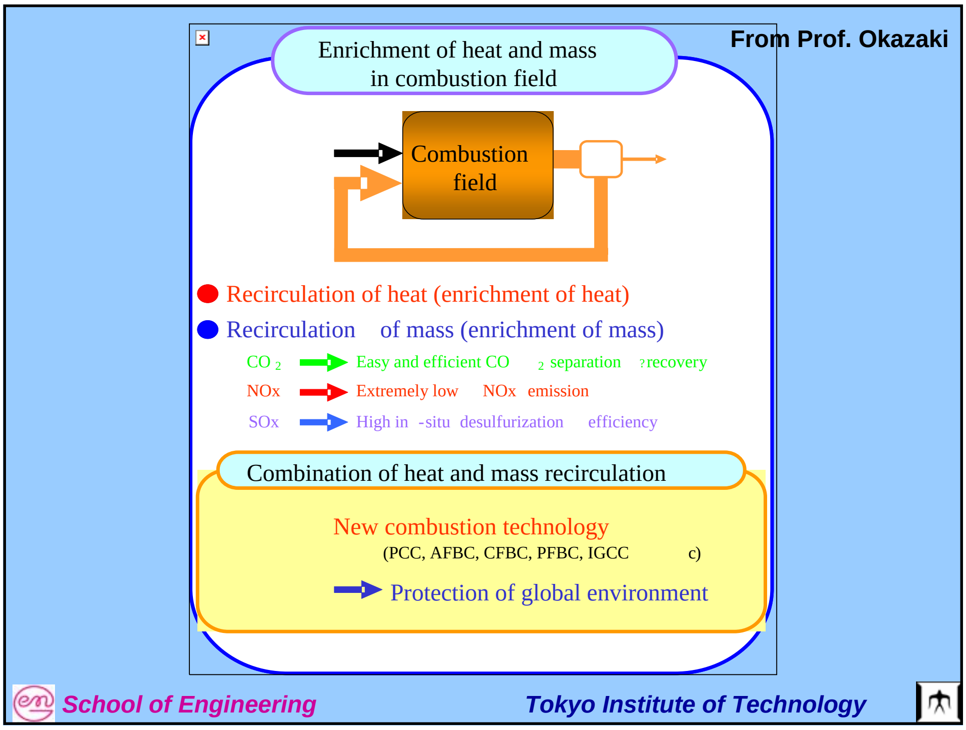


Various cases for CR* estimation

Cases	System	O_2 concentration (%)	Gas recirculation ratio according to chemical stoichiometry α	λ in volatile matter combustion zone
Case 1	Conventional pulverized coal combustion	21	0.0	0.7
Case 2	O_2/CO_2 pulverized coal combustion	30	0.77	0.7
Case 3	O_2/CO_2 pulverized coal combustion	21	0.84	0.7
Case 4	O_2/CO_2 pulverized coal combustion with about 40% heat recirculation	15	0.89	0.7




From Prof. Okazaki
Local desulfurization efficiency 0.35
Gas recirculation ratio: 0.84
Removed-S (CaSO4): 0.77 (mol/s)
Fuel-S (SO2): 1.0 (mol/s)
SO2 2.2 (mol/s)
1.43 (mol/s)
0.16
0.84
Exhausted-S: 0.23 (mol/s)
Recycled-S: 1.2 (mol/s)
System desulfurization efficiency: h = 77 %
Coal property (wt. %, dry)
C: 71.1 O: 8.86
H: 4.23 N: 1.76
S: 2.00
Calculation conditions
Oxygen-fuel ratio = 1.2, Temperature = 1400 K
one pass residence time = 8 s,CaIS = 5, CaCO3 (10 mm)
School of Engineering
Tokyo Institute of Technology


From Prof. Okazaki
Enrichment of heat and mass in combustion field
Combustion field
Recirculation of heat (enrichment of heat)
Recirculation of mass (enrichment of mass)
CO2 Easy and efficient CO2 separation ?recovery
NOx Extremely low NOx emission
SOx High in-situ desulfurization efficiency
Combination of heat and mass recirculation
New combustion technology
(PCC, AFBC, CFBC, PFBC, IGCC c)
Protection of global environment
School of Engineering
Tokyo Institute of Technology

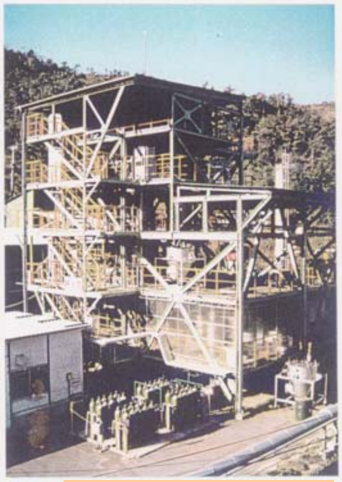
Combustion Test and CO_2 Compression Test

IHI

Combustion Test Facility

Capacity：1.2Mwt（Coal 150kg/h）

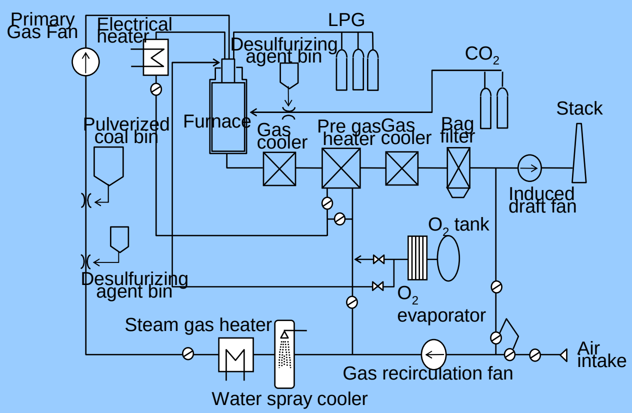
Furnace：Φ1.3m×7.5mL



IHI Test Facility - AIOI

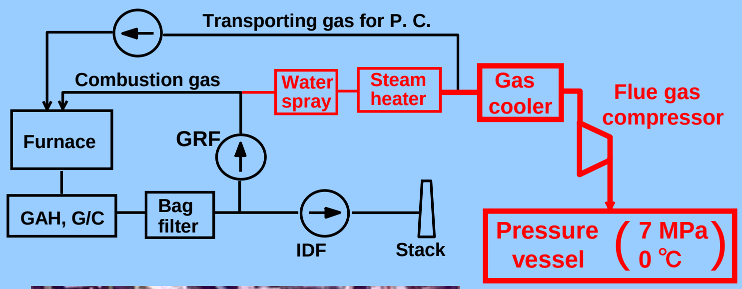
Oxy-firing Test Facility

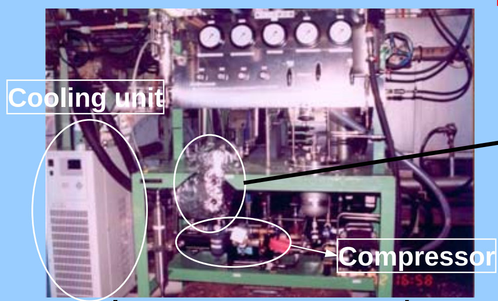
IHI



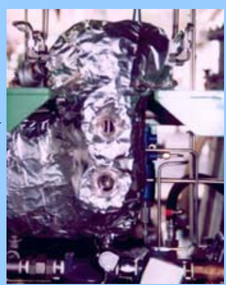
Flow diagram of industrial-scale combustion test facilities

Flue Gas (CO_2) Liquefied Test





Flue gas compressor unit

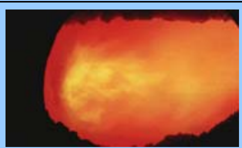


Pressure vessel

Results of Oxy-firing Test

Ignition/combustion characteristics

Flame of test facilities

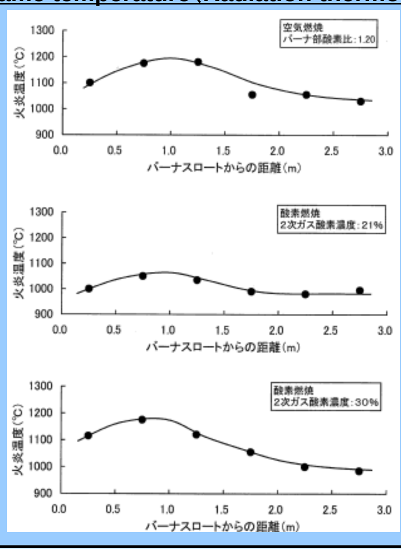


Air mode (O$_2$:21%)

Oxy mode (O$_2$:21%)

Oxy mode (O$_2$:30%)

Flame temperature (Radiation thermometer)

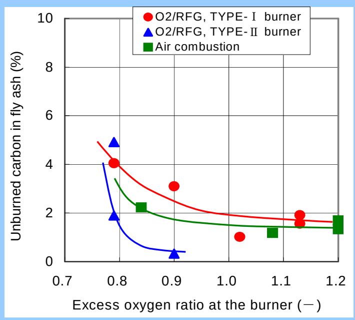


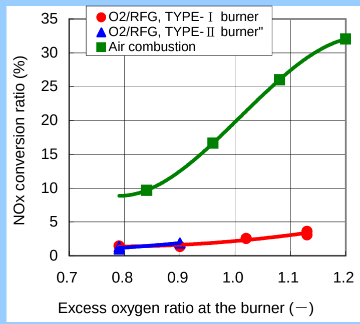
Result of Oxy-firing Test

IHI

Combustion condition
Coal : Coal A
Coal feed rate : 100 kg/h
Flue gas oxygen : 3.5%
Wind box oxygen : 30% (O_2/RFG combustion)
Pure oxygen flow rate : 20 Nm^3/h (O_2/RFG combustion)

Burner type (O_2/RFG combustion)
TYPE- I : Pure oxygen supply from the center of the burner
TYPE- II : Pure oxygen swirly supply from the center of the burner

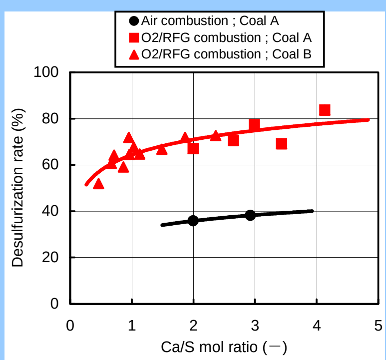




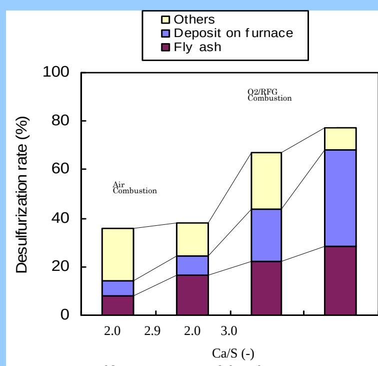
Result of Desulfurization Test

IHI

Combustion conditions
Coal : Coal A, B
Flue gas Oxygen : 3.5%
Coal feed rate : 100 kg/h
Wind box oxygen : 30%
Pure oxygen flow rate : 20Nm^3/h
Desulfurizing agent: $CaCO_3$



Comparison of desulfurization rate



Sulfur captured in the system

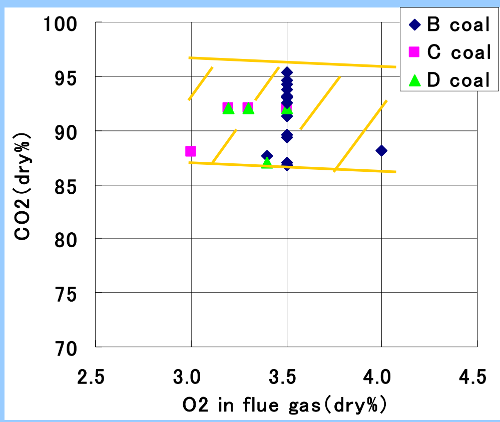
Ignition/Combustion Characteristics

IHI

CO_2 concentration

*1.2MWt combustion test facilities

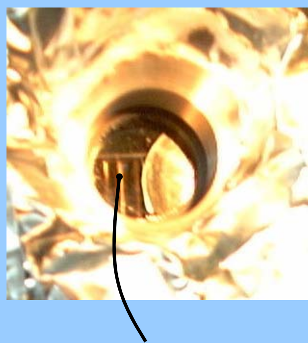
*85～95% CO_2 level



CO_2 recover and liquefaction

*Connection the compression equipment

*CO2 is recovered under 0℃／7MPa condition



Liquefaction of flue gas (CO_2)

Contents

IHI

1. Japanese Strategy for CO_2 Reduction
2. Oxy-firing Studies in Japan
3. **Study of 1000MW Class Oxy-firing Super-Critical Unit**
4. Japan-Australia Oxy-firing Project
5. Conclusion

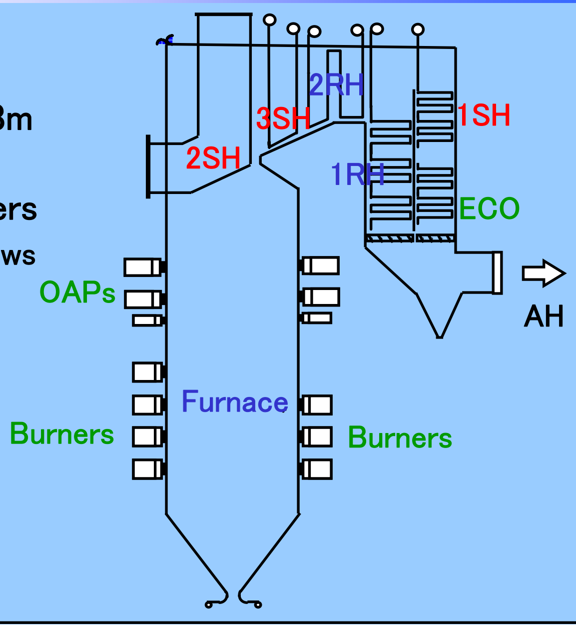
Basic Design of 1,000MWe Class Power Plant IHI

Boiler unit	1,000MWe output
Steam condition	24.1MPa, 538/566℃
Fuel	Coal (Bituminous coal)
	Light oil at the start up
Air separation unit	Cryogenic air separation
	58-100% range
Flue gas	Axial-type compressors
Compressors	20 MPa of outlet
Others	Base load unit
	Min. load 60%L (600 MWe)
	at Oxy-fuel combustion

Boiler Configuration IHI

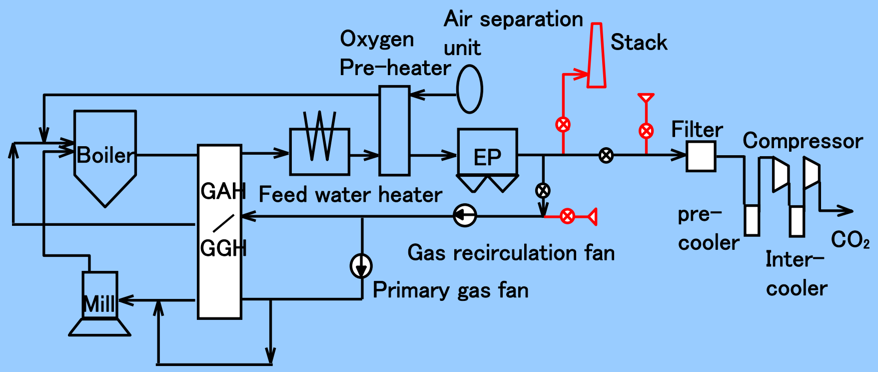
Furnace :
W33m/D15m/H68m

Burner :Total 56buners
*Front 4rows/Rear 3rows



Optimum System Flow

IHI



start up and shut down

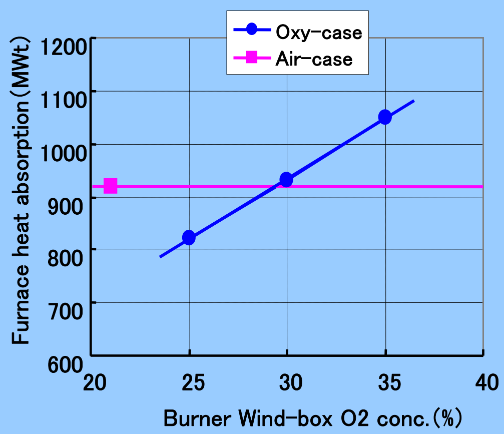
normal operation (O_2/RFG combustion)

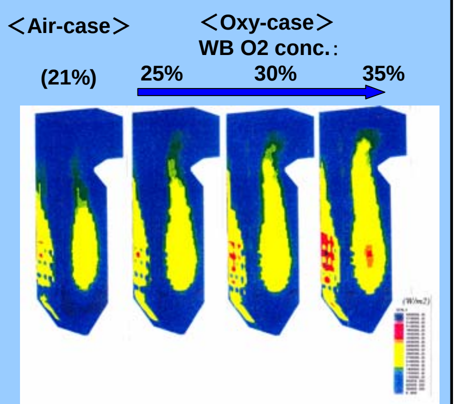
Furnace Heat Absorption

IHI

Boiler : 1,000MWe

Furnace : W33m × D15m × H68m





Heat absorption of 30% WB-O_2 in Oxy-case is the same value with air-case.

ASU and Compressors

IHI

ASU and flue gas compressors

※Boiler : 1,000MW class

<ASU>

Type : Cryogenic

O_2 purity : 97.5%.

Capacity : 90,000Nm^3/h class *5

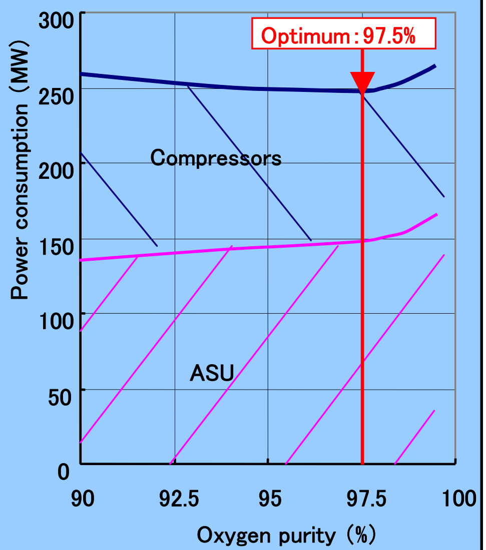
Outlet pressure : 30kPa

<CO_2 recovery equipment>

Type : Axial type

Outlet pressure : 20MPa

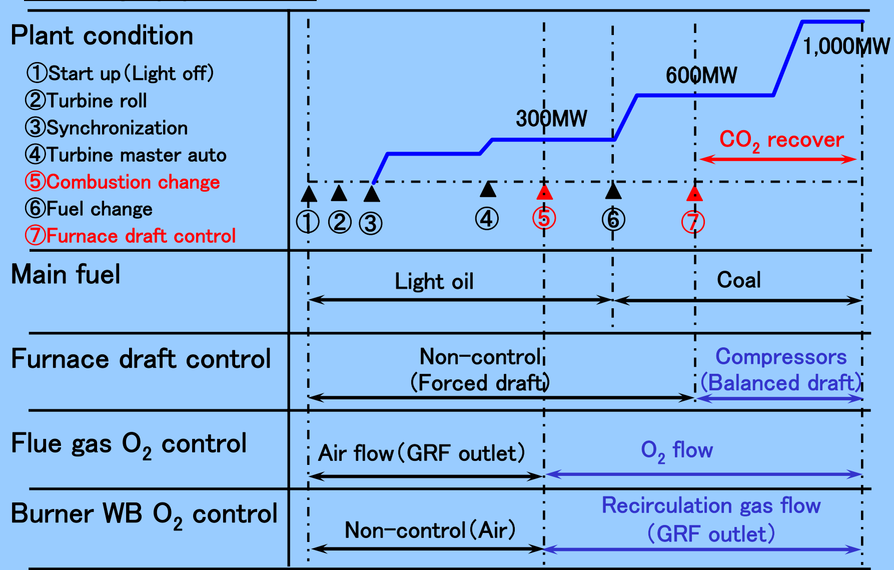
Capacity : 2 * 410t/h



Dynamic Plant Simulation

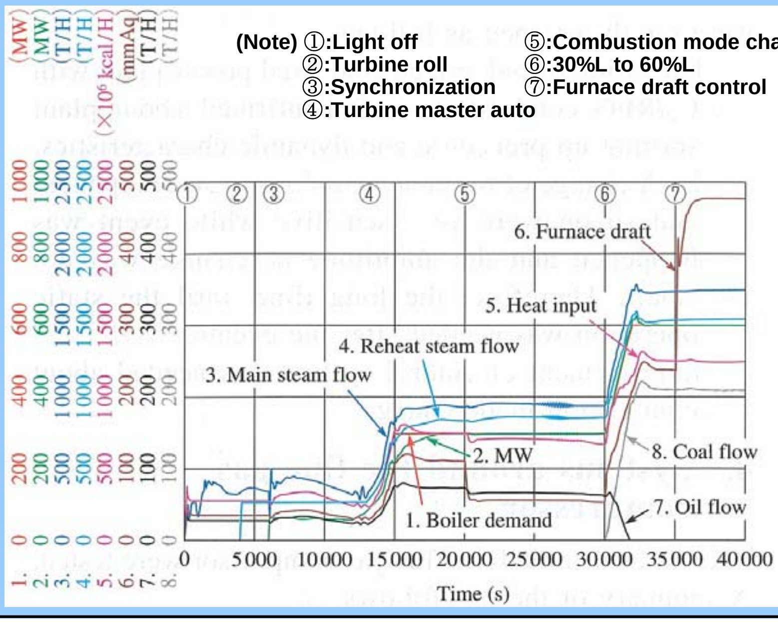
IHI

Starting up procedure



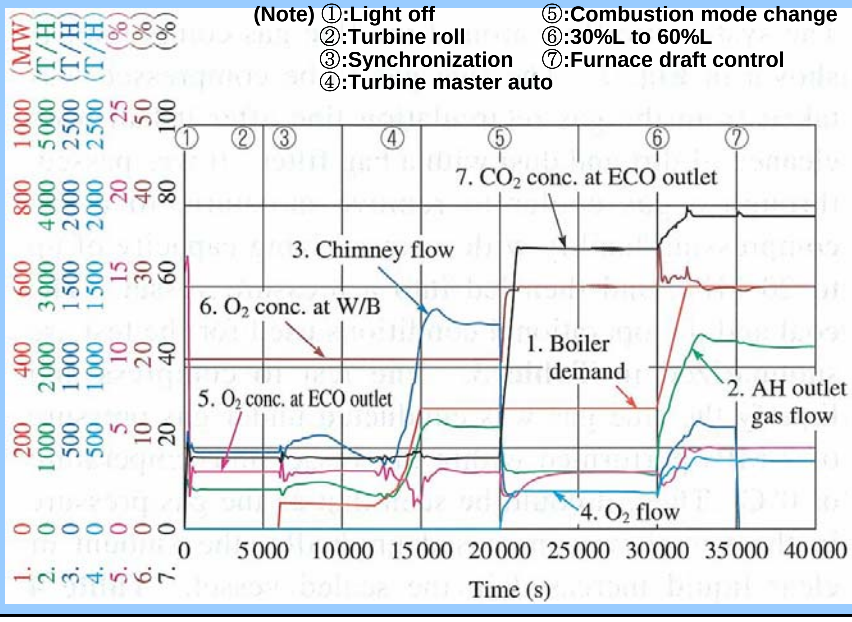
Dynamic Plant Simulation

IHI



Dynamic Plant Simulation

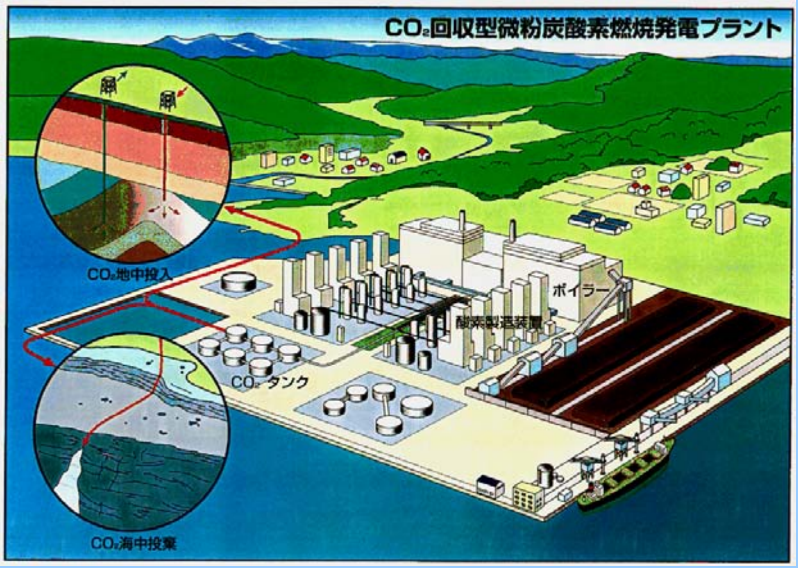
IHI



Basic Design

IHI

Image of 1000MW class PCF power plant with Oxy-fuel)



Contents

IHI

1. Japanese Strategy for CO_2 Reduction
2. Oxy-firing Studies in Japan
3. Study of 1000MW Oxy-firing Super-Critical Unit
4. **Japan-Australia Oxy-firing Project**
5. Conclusion

Japan/Australia Oxy-firing Project

IHI

Power plant site

Site : Queensland, Australia
Plant : CS Energy Callide-A No.4 unit
Output : 30MWe

Japan/Australia Oxy-firing Project

IHI

Overall Schedule

Items	2004	2005	2006	2007	2008	2009	2010	2011
FS of Aus./Japan Project								
Design, conversion, operation of demonstration plant								
Commercial plant								

Contents

IHI

Conclusion

IHI

1. **Oxy-firing : one of the simplest ways to reduced CO_2**
2. **Many Oxy-firing projects in many places go together hand in hand**

Acknowledgement:

All the tests except done in TIT were funded by NEDO.

Inaugural Workshop

International Oxy-Combustion Research Network

Vattenfall Europe Mining and Generation AG Head Office
Cottbus, Germany

29th and 30th November 2005

PRESENTATION - 01

Oxy-Fuel Combustion Application for Coal Fired Power Plant: What is the Current State of Knowledge

by:

Stanley Santos
IEA Greenhouse Gas R&D Programme, UK

This page is intentionally left blank

IEA Greenhouse Gas R&D Programme

Oxy-Fuel Combustion Application for Coal Fired Power Plant

What is the Current State of Knowledge…

Stanley Santos and Mike Haines

IEA Greenhouse Gas R&D Programme

Inaugural Workshop
IEAGHG International Oxy-Fuel Combustion Network

Vattenfall Europe Mining and Generation AG
Cottbus, Germany
29th November 2005

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

Highlights to the History of Oxy-Fuel Combustion Application

1940 – 1950

High Temperature Applications
- Welding
- Metal cutting
- Flame Polishing

1960 – 1970

Productivity Enhancement via O2 Enrich Combustion (OEC)
- Glass, Aluminium & Cement industries

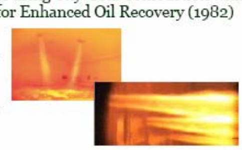
1980 – 1990

Fuel Savings – Emergence of full Oxy-Fuel Combustion Application
- waste incineration
- steel and copper industries

Idea of using Oxy-Coal Combustion with RFG for Enhanced Oil Recovery (1982)

1990 – 2000

NOx Reduction
- glass melting furnaces
- OEC coal fired boilers



2000 – 2010?

CO_2 Reduction
- Power Generation industry
  - IGCC & OxyFuel boiler applications

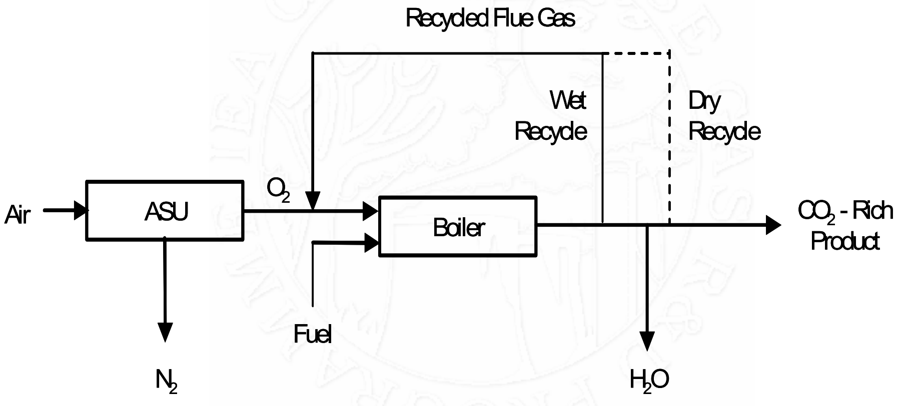
Adapted from slide of Sho Kobayashi, Praxair

Pictures from IFRF, Air Liqiude, Asahi Glass, Linde Gas

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

Oxy-Coal Combustion with Recycled Flue Gas (RFG)



www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

Overview to Oxy-Coal Combustion/RFG Study

- 1982: Initial suggestion by Abraham et. al. (1982) of using Oxy-Coal Combustion to produce CO_2 for EOR
- 5 major pilot scale studies between 1980 - 2000
  - ANL – EERC (3 MW)
  - EU – IFRF
    - IFRF (2.5 MW)
    - MBEL – Air Products – Naples & Ulster University (150 kW)
    - Rolls Royce (IC) – Imperial College – EDP – IST (150kW & 35MW)
  - NEDO – IHI (1.2 MW)
  - CANMET (300 kW)
  - US DOE – B&W / Air Liquide (1.2 MW)

www.ieagreen.org.uk

Presentation Outline

- Study Report on Oxy-Fuel Combustion
  - Study commissioned by IEAGHG (Report No.: 2005-9)
  - This study was led by Mitsui Babcock
- Considerations, Development and Demonstration
  "**What is the Current State of Knowledge**"
- Concluding Remarks

IEA Greenhouse Gas R&D Programme

Oxy-Combustion of Coal

Findings from study report by

Mitsui-Babcock
Alstom
Air Products

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

Oxy-combustion of coal for CO_2 capture

- IEAGHG study led by Mitsui Babcock
- Published June 2005
- Covers both coal and gas fired options

- This presentation will cover:
  - Coal fired pulverised fuel oxy-combustion
  - Main findings of study report

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

Basis and scope

- Coal fired power station 500MWe nominal output
- Pulverised fuel, supercritical boiler base case
- Comparison of capture with non-capture case
- Conservative design – no technology stretch
- Define basic flow schemes and process conditions
- Capital and operating cost estimates
- Economic analysis

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

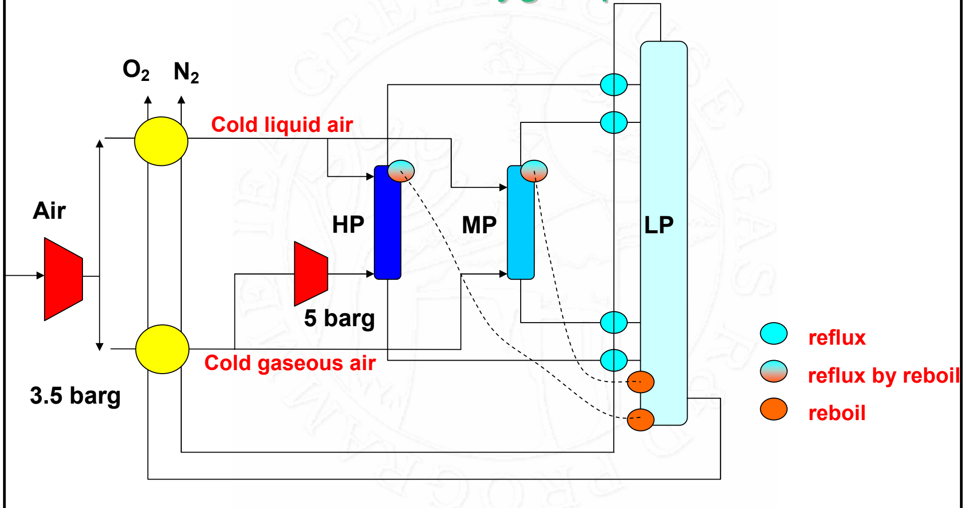
Oxygen supply

- Oxygen production in HP/MP/LP 3 column system – power reduced to 201kwh/ton
- Optimum oxygen purity – *(previous studies)*
  - 95% chosen -higher purity not worthwhile due to:
    - Excess O_2 requirement (19%)
    - Boiler air in leakage (1%)
    - ESP air in leakage (2%)
- Two trains of 5200 t/d oxygen each
- Two levels of air compression *(saves power)*

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

3 column oxygen plant



www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

CO_2 Recycle Streams

- Recycle equivalent to ~30% O_2 in CO_2
- 37% of CO_2 recycle dried and fed to coal mills
- 63% fed to burners
  - Part mixed with Oxygen to max 23% O_2
- Balance fed direct to burner/furnace
- Recycle cooled to 270ºC
  - Compromise between efficiency and cost of ESP *(Electrostatic precipitator)*

www.ieagreen.org.uk

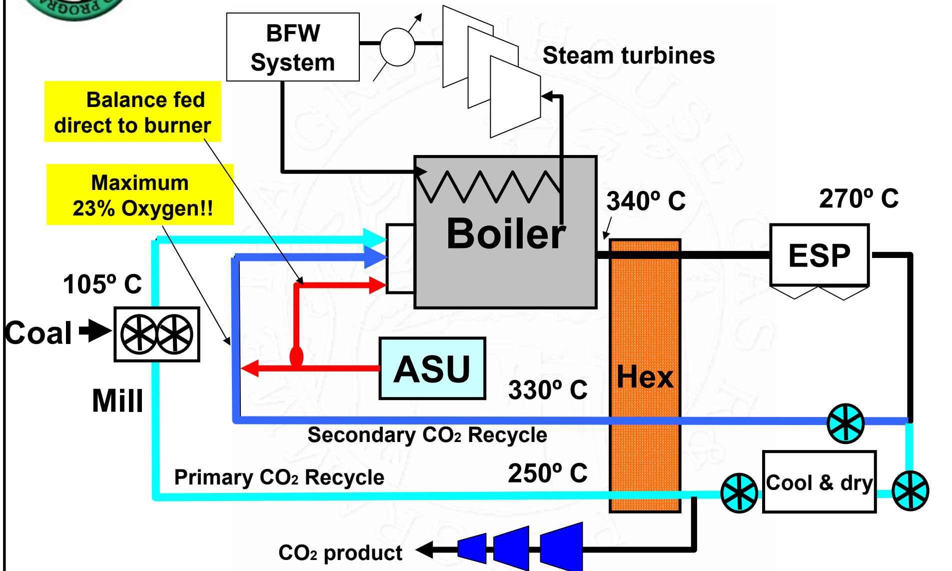
IEA Greenhouse Gas R&D Programme

CO_2 Recycle Streams

- Primary recycle to coal mills
  - Cooled, scrubbed, dried and reheated to 250ºC in recuperator. (SO_3 free)
  - Exit mills at 105ºC
- Secondary recycle to burners
  - Cleaned (ESP) at 270ºC
  - Reheated in recuperator to 330ºC
- Recuperator
  - Flue gas in at 340ºC exits to ESP 270ºC

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme



www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

Other design points

- BFW heating from:
  - ASU main air compressor
  - CO_2 compressor
- No buffer storage for oxygen
- Plant designed for oxygen operation only
- Start-up operation based on air fired operation at reduced capacity
- High temperature ESP design needs to consider effect of ash resistivity

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

CO_2 clean up

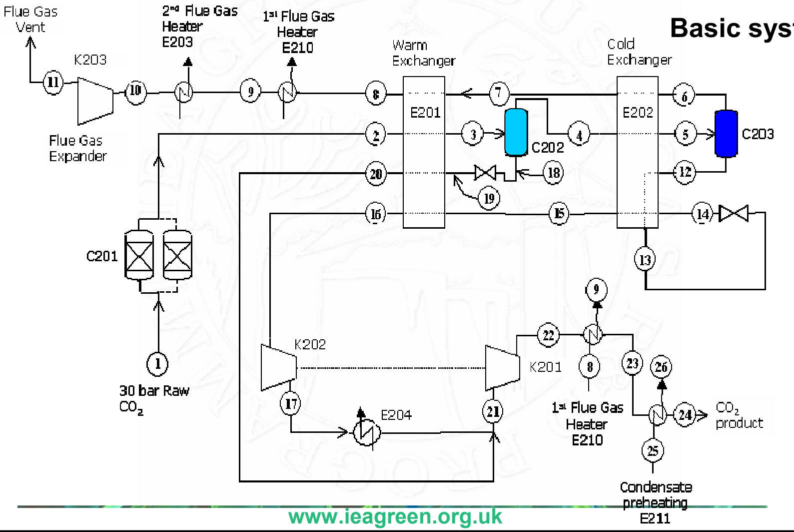
- CO_2 clean up
  - CO_2 purified to 95% (optionally 98%)
  - Cryogenic process using two flashes to reduce non-condensibles *(extra flash and compression for 98%)*
  - SO_2 and NOx not removed
  - Simple distillation can replace flash system to remove SO_2 and NOx

www.ieagreen.org.uk

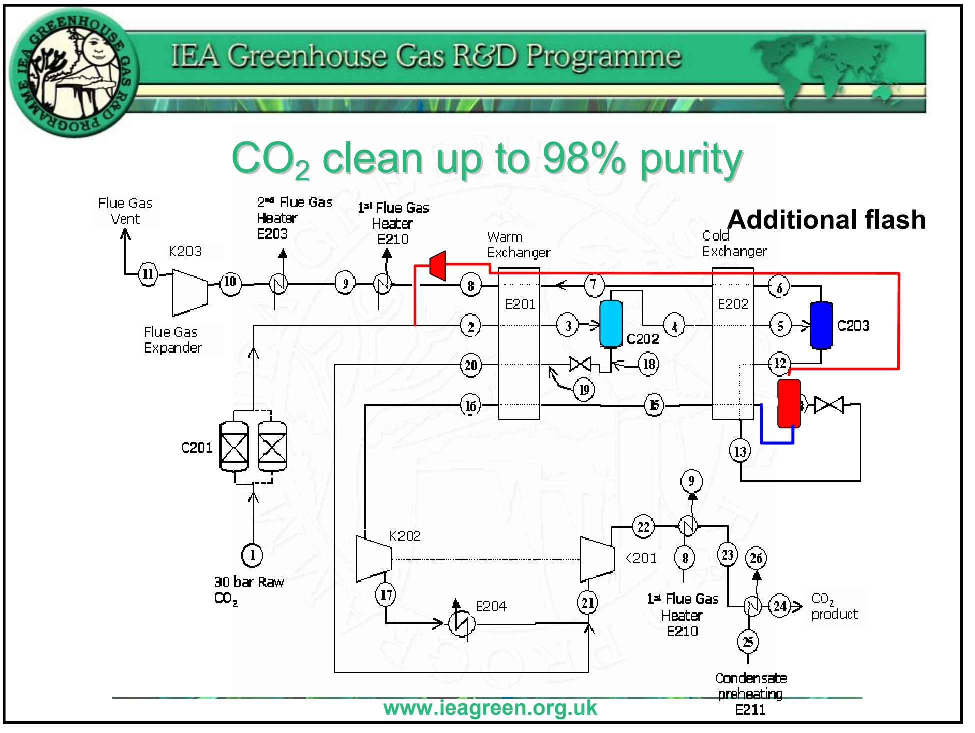
IEA Greenhouse Gas R&D Programme

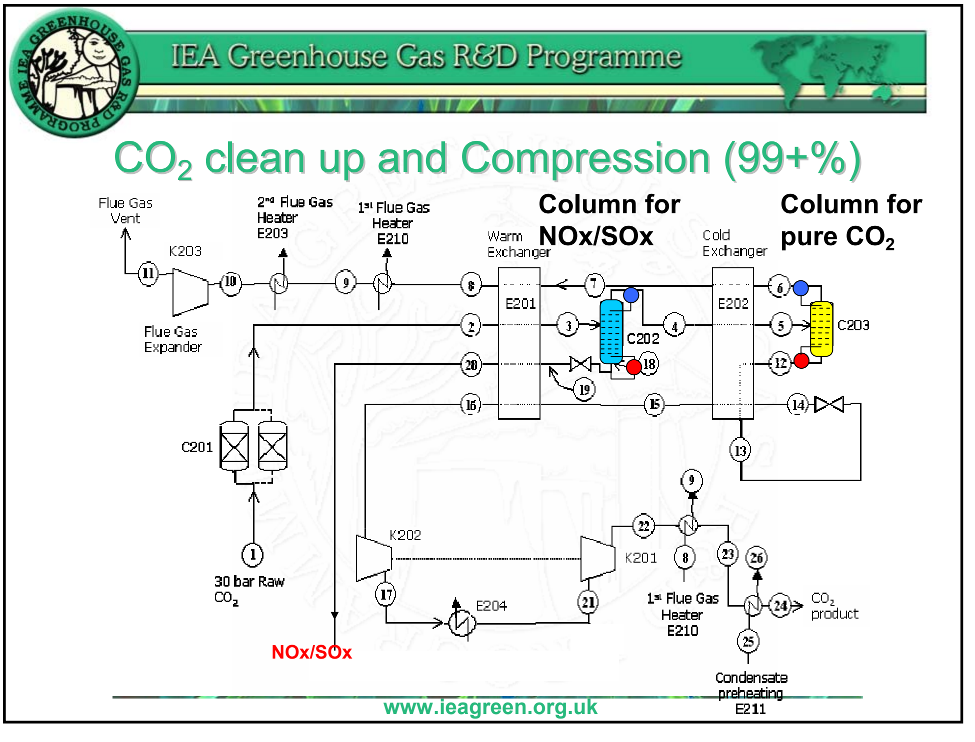
CO2 clean up and Compression (95%)

Basic system



www.ieagreen.org.uk


IEA Greenhouse Gas R&D Programme
CO2 clean up to 98% purity
Additional flash
Flue Gas Vent
2nd Flue Gas Heater E203
1st Flue Gas Heater E210
Warm Exchanger
Cold Exchanger
K203
Flue Gas Expander
E201
E202
C202
C203
C201
30 bar Raw CO2
K202
K201
E204
1st Flue Gas Heater E210
CO2 product
Condensate preheating E211
www.ieagreen.org.uk


IEA Greenhouse Gas R&D Programme
CO2 clean up and Compression (99+%)
Column for NOx/SOx
Column for pure CO2
Flue Gas Vent
2nd Flue Gas Heater E203
1st Flue Gas Heater E210
Warm Exchanger
Cold Exchanger
K203
Flue Gas Expander
E201
E202
C202
C203
C201
30 bar Raw CO2
K202
K201
E204
NOx/SOx
1st Flue Gas Heater E210
CO2 product
Condensate preheating E211
www.ieagreen.org.uk

Performance and costs (coal)

Assumptions and Basis of Calculation - Handouts

Cost of power ¢ / kwh

Base case	Oxy-combustion	Pre/Post
4.4	6.1	6.3

Net efficiency %

	Base case	Oxy-combustion
	44.3	35.4
Gross MW	740	737
Net MW	677	532

Development and Demonstration Issues to Consider

IEA Greenhouse Gas R&D Programme

Development and Demonstration

- Oxygen Production
- Coal Preparation
- Recycle Flue Gas Clean Up
- Burner and Boiler Development
- Product CO_2 Clean Up
- Process Operation, Safety and Integration

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

Oxygen Production

- Oxygen Production via cryogenic process is considered a mature technology.
- Challenges…
  - How to further reduce cost and power consumption
  - Uses of by-product gases (ie. Ar, N_2 etc…)
- What is the future in the development of other novel oxygen production processes…

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

Coal Preparation and Recycle Flue Gas Clean-Up

- Coal preparation:
  - Verify operation on recycle flue gas
  - Acceptable dust loading and moisture content of the recycle flue gas without hampering milling operation
- ESP:
  - Check designs for high temperature operations
  - Unforeseen corrosion problems due to recycle flue gas
  - Air in-leakage minimisation
- Emergency vent: after the boiler island / CO_2 clean-up
  - Design for fast acting, low leakage vent valve

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

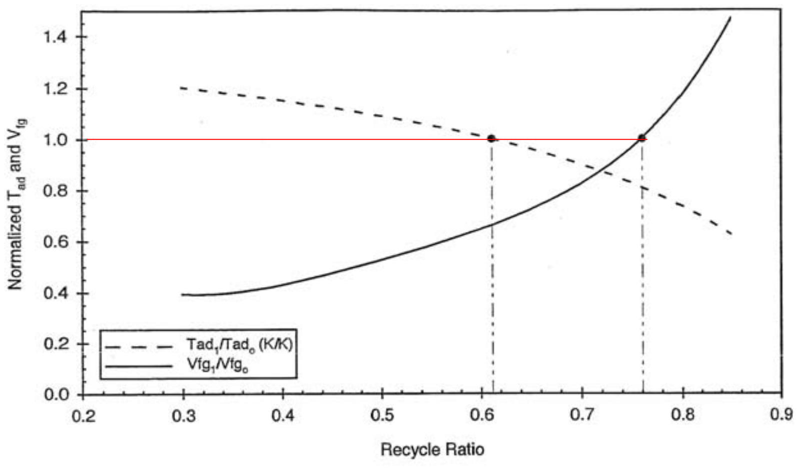
Burner and Boiler Development

- Heat Transfer
- Combustion
- Ash Handling
- Operation and Safety
- Environment
- Other Issues
  - boiler and refractory material, combustion control, flame detection etc…

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

Adiabatic Flame Temperature and Flue Gas Volume as Compared to Recycle Ratio



IEA Greenhouse Gas R&D Programme

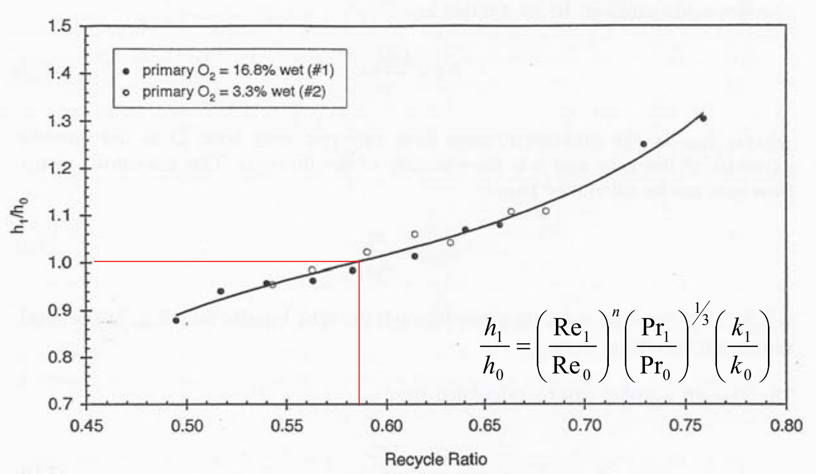
Burner and Boiler Development: Heat Transfer

- Early studies done during 80's and 90's focused on Heat Transfer Study for Boiler Retrofit.
- Consideration should looked at:
  - Convection Heat Transfer
  - Radiative Heat Transfer

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

Ratio of Convective Heat Transfer Coefficient



Effect of Recycle Ratio on Convective heat transfer coefficient [IFRF APG1 Trials]

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

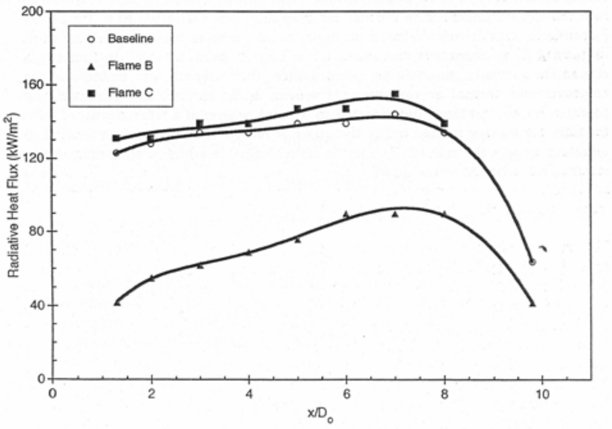
Optimum Recycle Ratio

- ANL – EERC
  - Wet: R = ~ 0.68 $[CO_2 + H_2O]/[O_2]$ = 3.25
  - Dry: $[CO_2 + H_2O]/[O_2]$ = 2.66
- IFRF
  - Wet: R = ~ 0.58 $[CO_2 + H_2O]/[O_2]$ = ~2.4
- Critical factors that may affect on these values:
  - Amount water in the flue gas
  - Amount of air in-leakage

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

Radiative Heat Flux Measurements



Radiative Flux Using Ellipsoidal Radiometer in Air (Baseline) and O_2/RFG (Flames B with recycle ratio = 0.73 and Flame C with recycle ratio = 0.58) – IFRF APG2 Trials

Ellipsoidal Radiometer Results were also obtained by:

- ANL-EERC
- CANMET

Data from Narrow Angle Radiometer is necessary for radiation modelling development

Knowledge gap is in the radiation factor contribution of solid particles in the furnace

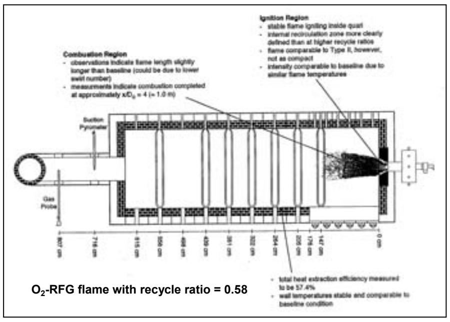
www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

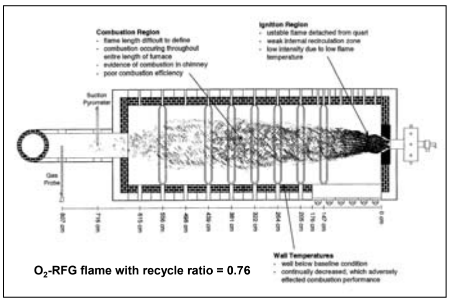
Burner and Boiler Development: Combustion

- Studies have established that there is a limit for the amount flue gas that can be recycled.
- Lower recycle ratio results to a very short intense flame could be observed. (issues regarding burner material construction should be considered when operating at this condition).
- Studies have noted that no significant change on the ignition and combustion of coal when using recycle flue gas as "transport air"
- Burner Scaling – Is there a requirement for a more detailed study?

www.ieagreen.org.uk



Recycle Ratio = 0.58
(~ 0.61 include the CO_2 to transport coal)



Recycle Ratio = 0.76

IEA Greenhouse Gas R&D Programme

Burner and Boiler Development: Combustion

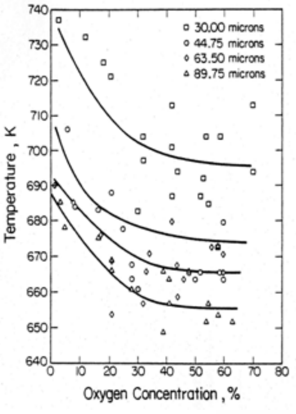
- AASB burner used by IFRF – well understood in terms of scaling and NOx emission (under the IEA Annex Programme). What can we learn from this study?
- Several In-Flame Measurements Data in various literature
  - ANL-EERC: temperature, composition (CO_2, CO, SO_2, NOx), UBC, radiant heat flux, wall emissivity)
  - IFRF: temperature, composition, velocity, radiant heat flux.
  - MBEL: temperature, composition
  - IHI: temperature, composition (including NH_3, HCN)
  - CANMET: temperature, composition, radiant heat flux

www.ieagreen.org.uk

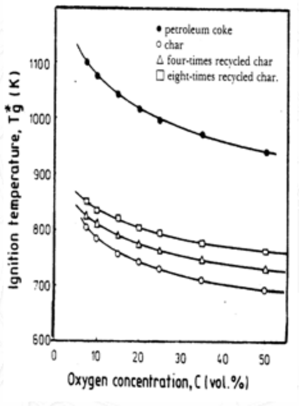
Coal Combustion Properties

- Most coal used in early studies ranges from Sub-Bituminous to Bituminous Coal.
- Necessary to develop understanding of oxy-firing characteristics on brown coal.
- Fundamental data (ie. Devolatilisation / Char burnout) are still necessary for kinetic data and validation for CFD modelling

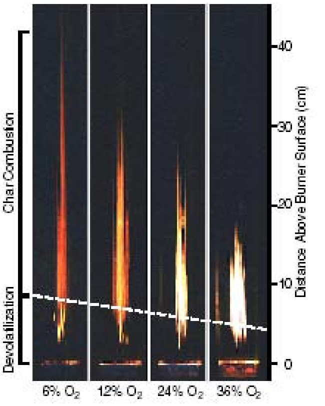
Effect of Oxygen Enhancement on Coal Combustion



Variation of ambient gas temperature at ignition with oxygen concentration [Brook and Essenhigh, 1986]



Ignition temperature of petroleum coke and char with O_2 concentration [Rybak et. al. 1986]



Time lapse photographs of Highvale coal combustion in an entrained flow reactor at various oxygen enhancement level (Shaddix and Murphy 2001)

IEA Greenhouse Gas R&D Programme

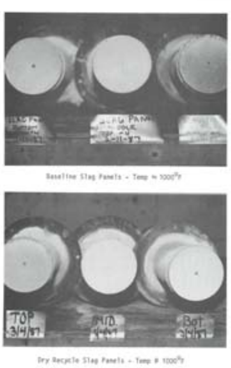
Burner and Boiler Development: Ash Related

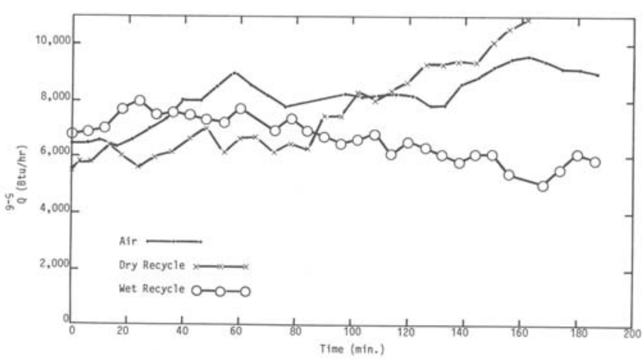
- Issues regarding slagging and fouling should be elucidated. This is especially required when dealing with coal of high slagging propensity.
- Further information are still necessary regarding composition of ash, size distribution, ash morphology, slagging and fouling propensity etc…
- Effect of oxy-firing on the fly ash
  - Consideration to its pozzolanic activity. Studies by MBEL/Air Products indicated no significant change. Is this true to all types of coal?
- For plant retrofit – volume of flue gas will be lower when operating at optimum flue gas recycle ratio.
  - Will there be any issue regarding operation of soot blower (ie. loss of sand blasting effect)

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

Ash Related Issue





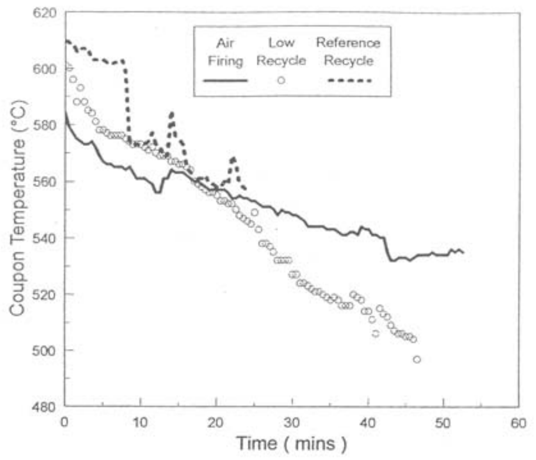
Black Thunder Coal

Data from ANL-EERC Trials

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

Ash Related Issue



Data from the trials taken by:

MBEL, Air Products, Ulster University and Naples University (1995)

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

Burner and Boiler Development: Emissions

- Final clean-up of the product flue gas will depend on final utilisation or storage of the product flue gas.
- NOx and SO_2 have been reported to be lower in various studies.
  - Formation mechanism has been investigated during the NEDO / IHI study.
- Issues on the level of SO_3 should be clarified.
- Also some literature reporting lower Hg emission. This will require confirmation.
- Issues related to particulate emission is important in the final clean up of the flue gas.

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

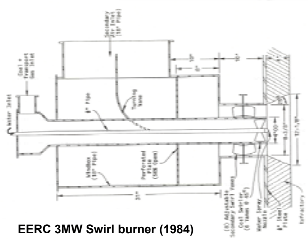
Operation and Safety

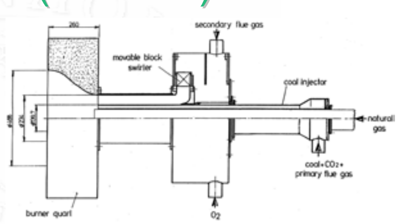
- Turn Down Operation
  - ANL-EERC Study presented turn down operation to 1.5 MW (50% load) for Black Thunder Coal and Utah
  - Safety issue regarding flame blowout and explosion has been noted.
  - IFRF Study has achieve turn down operation of 70% load. The limitation is also on safety issue.
- Start Up Operation
  - Experience gained during the operation of 35MWth by International Combustion Ltd. (2 options were presented).
  - Successful start-up have been noted by B&W and Air Liquide Study
- Air Ingress into boiler.
  - Recommended that air ingress should be less than 3% to achieve 90+% level.

www.ieagreen.org.uk

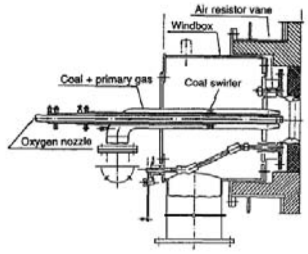
IEA Greenhouse Gas R&D Programme

Burners Type (> 1 MW)

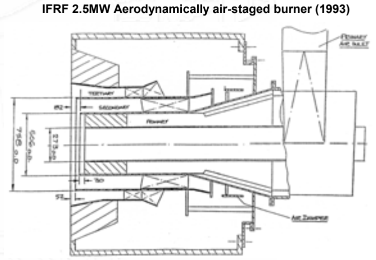

EERC 3MW Swirl burner (1984)



IFRF 2.5MW Aerodynamically air-staged burner (1993)



IHI 1.2MW$_{th}$ coal swirl burner (1995)


35MW$_{th}$ low NOx Dual Register Burner (1994)

www.ieagreen.org.uk

Comment on Burner Studies

- Most burners used in the different major pilot scale studies undertaken during the early studies make use of Swirl Type Coal Burner
- These burners are typically used for Wall Fired Boilers
- Is there a need to investigate burners used for Tangential or Corner Firing Boilers?… (ie. long coal flame)?
- Which is the most appropriate burner and boiler configuration?

CO_2 Clean Up and Process Operation

- CO_2 clean up:
  - Optimise design for CO_2 recovery
  - Design for NOx/SOx recovery
  - Practical uses for recovered NOx/SOx
- Start-up and shutdown:
  - Detailed sequences
  - Optimise/minimise O_2 storage requirement
  - Establish purging procedures

IEA Greenhouse Gas R&D Programme

Process Operation, Safety and Integration

- Dynamics between O_2 Production, Boiler Operation and CO_2 Clean Up will require understanding. Which Process is the bottleneck?
- Control:
  - Establish load following requirements and design basic control system
  - Establish trip system requirements
  - Analyse interactions between plant segments
  - Design to avoid cascade events

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

Concluding Remarks

- Oxy-combustion of coal for CO_2 capture is competitive with other options
- Retrofitting boilers and burners for oxy-coal combustion are technically feasible.
- Study noted there are necessary development requirements in the aspects of:
  - Plant Start Up
  - Burner and Boiler Development
  - Material Issues
- Development Area Identified are No Show Stoppers!!!

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

Concluding Remarks

- Fundamental studies – still necessary for coal combustion
  - devolatilisation and char burnout
  - ash characteristics
- Heat transfer issues
  - Data requirement for validation of radiation modelling
  - Further understanding regarding the effect of flue gas recycle ratio to the heat transfer parameters is still necessary.

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

Concluding Remarks

- Operation challenge for burners and boilers include:
  - Start-up operation / sequence
  - Turn down operation
  - Air Ingress
  - Development in refractory materials for furnace
  - High temperature corrosion issue
- Requirements to address safety issues.
  - development in combustion controls
  - development in flame monitoring techniques
- Environmental issues
  - Requirements on issues regarding NOx, SOx, Hg and particulates should be addressed.

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

Where are we now…

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

Oxy-Coal Firing Projects

- Current News of 2005:
  - Alstom recently announced the completion of oxy-CBF (3MW) test.
  - 3 new project awarded by US DOE in 2005
    - Southern Research Institute – investigate various aspect regarding retrofitting coal fired power plant
    - B&W Project - 5 Million Btu test on wide ranging coal (Eastern Bituminous, PRB, Sub-Bituminous, Lignite)
    - BOC Project – Oxyfiring combustion with incorporation of CAR
  - ADECOS Project – under COORETEC (coordinated by TU Dresden) – Launched in June 2005.
  - Announcement by TOTAL regarding OxyFiring Project in Lakse.

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

Future Generation Oxy-Coal Burner???

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

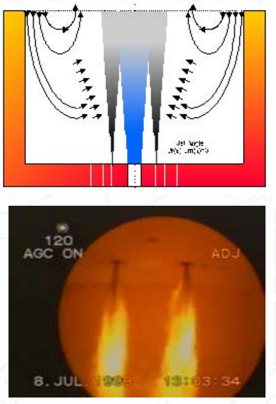
Development of Internally Recirculated Flue Gas

- Technologies for Oxy-Gaseous / Liquid Fuel Combustion used in Glass and Metal Industries are considered mature.
- Several techniques has been developed for controlling heat transfer and flame temperature profile
- There is a competition between Oxy-Fuel Combustion and Low NOx Rapid Cycling High Temperature Air Regenerative Combustion.

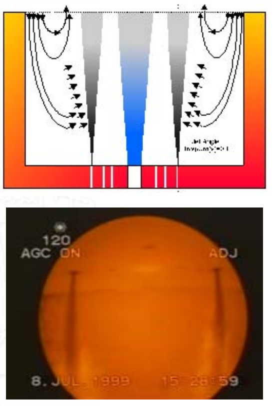
www.ieagreen.org.uk

High Temperature Air Combustion for Coal

- Based on a principle of a perfectly well stirred reactor / high velocity jet burners
- IFRF has demonstrated the technical feasibility of high temperature air combustion for coal.
- Comburrent temperature is greater than 1200°C yet peak temperature in furnace is only about 1550°C.
- Internally recirculated flue gas oxy-coal combustion will adapt to this technique.



Configuration 1



Configuration 3

Data and Picture from IFRF

IEA Greenhouse Gas R&D Programme

Acknowledgement

- Acknowledge the Mike Haines and John Davison for the preparation of this presentation.

- E-Copy of this report is now available – I have limited number of copies in CD. Approach me during the tea breaks.
- Future Studies:

CO_2 Capture in Low Rank Coal Power Plants
Study Report by Foster Wheeler

Now under Review – Will be release early next year.

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

Acknowledgement

- Presentation is based on an update to the review paper me and my colleagues completed whilst working with International Flame Research Foundation
- IFRF Document No.: G123/y/1
  F98/y/1; F98/y/2 and F98/y/4
- Contact:
  - Neil Fricker, Interim Director - IFRF
  - Email: neil.fricker@ifrf.net
  - Tel. No.: +31 251 291 600
- European Commission Joule II Clean Coal Technology Program 1992 – 1995. Volume II: Powder Coal Combustion Projects Final Reports. ISBN 92-9-828-006-7.

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

Extra Slides If Time Permits

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

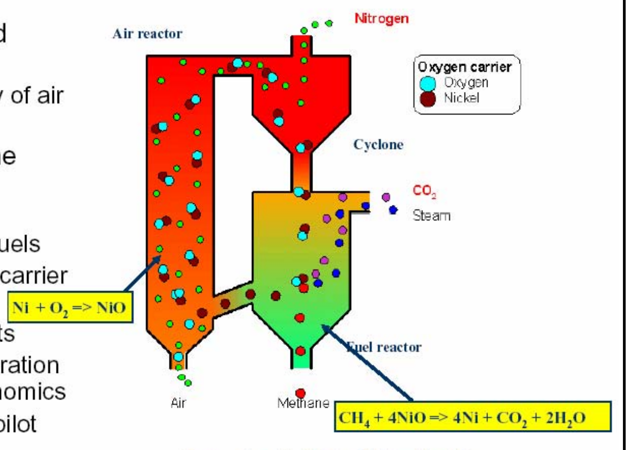
Future Development

Novel Oxy-Fuel Combustion Technique for Solid Fuel

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

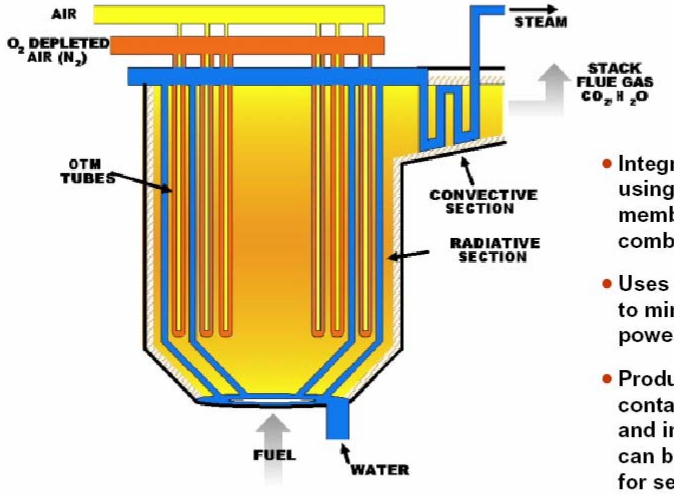
- Combustion with a solid "oxygen carrier"
  - avoids energy penalty of air separation
- Developments within the ENCAP project
  - Chemical looping combustion for solid fuels
  - Evaluation of oxygen carrier materials
  - Novel reactor concepts
  - Process design, integration optimisation and economics
  - Phase 2 decision on pilot testing



Courtesy Jens Wolf, Vattenfall Utveckling AB

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme



- Integrates air separation using oxygen transport membranes and combustion
- Uses chemical potential to minimize air separation power required
- Produces flue gas containing only CO_2, H_2O and inerts from fuel that can be readily cleaned up for sequestration.

PRAXAIR

www.ieagreen.org.uk

IEA Greenhouse Gas R&D Programme

Future Activities

- There are many other new developments…
- Are we going for a multi-theme oxyfuel combustion network?
- Are we ready to set up a workshop especially for new developments?

www.ieagreen.org.uk

This page is intentionally left blank

Inaugural Workshop

International Oxy-Combustion Research Network

Vattenfall Europe Mining and Generation AG Head Office
Cottbus, Germany

29th and 30th November 2005

PRESENTATION - 02

Fundamentals of Oxy-Fuel Combustion

by:

Prof. Terry Wall
University of Newcastle, Australia

This page is intentionally left blank

Fundamentals of Oxy-Fuel Combustion

Prof Terry Wall

Chemical Engineering, University of Newcastle, 2308, Australia

Oxy-fuel Combustion Research Network

Vattenfall Europe, Cottbus, Germany, 29/30 November 2005

CCSD

Focus of presentation

Based on recent review……

B.J.P. Buhre, L.K. Elliott, C.D. Sheng, R.P. Gupta, and T.F. Wall, Oxy-Fuel Combustion Technology For Coal-Fired Power Generation, Progress in Energy and Combustion Science, 31, 283-307, 2005

….. with a focus on a retrofit, that is, a comparison between air and oxy-fuel firing

….. using literature and some of our own research.

CCSD

Differences between oxy-fuel combustion and air combustion, identified in PECS review (31, 283-307, 2005).

To attain a similar adiabatic flame temperature the O2 proportion of the gases passing through the burner is higher, typically 30%, higher than that for air of 21%, and necessitating that about 60% of the flue gases are recycled.

The high proportions of CO2 and H2O in the furnace gases result in higher gas emissivities, so that similar radiative heat transfer for a boiler retrofitted to oxy-fuel will be attained when the O2 proportion of the gases passing through the burner is less than 30%.

The volume of gases flowing through the furnace is reduced somewhat, and the volume of flue gas (after recycling) is reduced by about 80%.

The density of the flue gas is increased, as the molecular weight of CO2 is 44, compared to 28 for N2.

Differences between oxy-fuel combustion and air combustion, contd:

Typically, when air firing of coal, 20% XS air is used. Oxy-fuel requires an % excess O2 (defined as the O2 supplied in excess of that required for stoichiometric combustion of the coal supply) to achieve a similar O2 fraction in the flue gas as air firing, in the range of 3 to 5%.

Without removal in the recycle stream, species (including corrosive sulfur gases) have higher concentrations than in air firing.

Oxyfuel combustion combined with sequestration must provide power to several significant unit operations, such as flue gas compression, that are not required in a conventional plant without sequestration, oxyfuel combustion / sequenstration is less efficient per unit of energy produced. However, it is more efficient than a conventional plant with sequestration due to the significant energy required to scrub a dilute gas stream prior to compression.

Identified issues covered

Heat transfer
- radiative transfer of furnace
- convective transfer in convection pass

Coal reactivity
- devolatilisation
- char reactivity

Emissions
- NOx
- SOx
- trace elements

Other
- ash impacts - fouling, slagging, ash collection
- modelling

……. With a summary of significance and status

The University of Newcastle

CCSD

Heat transfer

Sameer Khare, Raj Gupta, Terry Wall

CRC for Coal in Sustainable Development

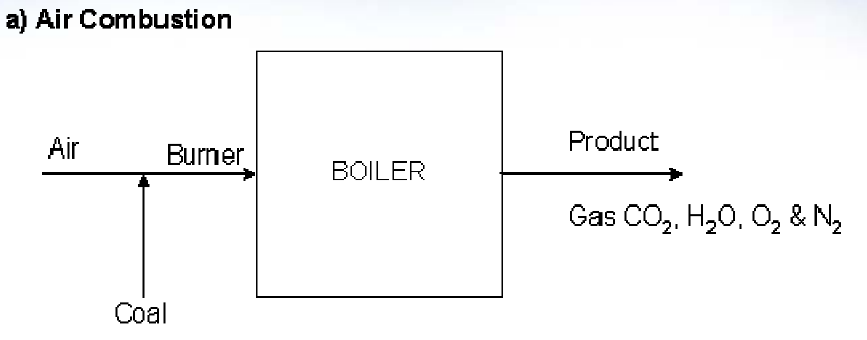
University of Newcastle

….. focusing on O2 thru the burners to match heat transfer

CCSD

Conventional System Design

Air-Case

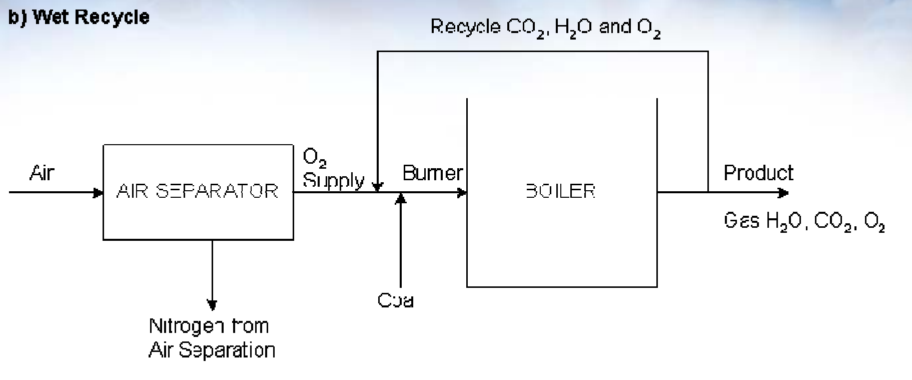


20% XS air ~ 3% O2 in product (flue) gas, used for control

CCSD

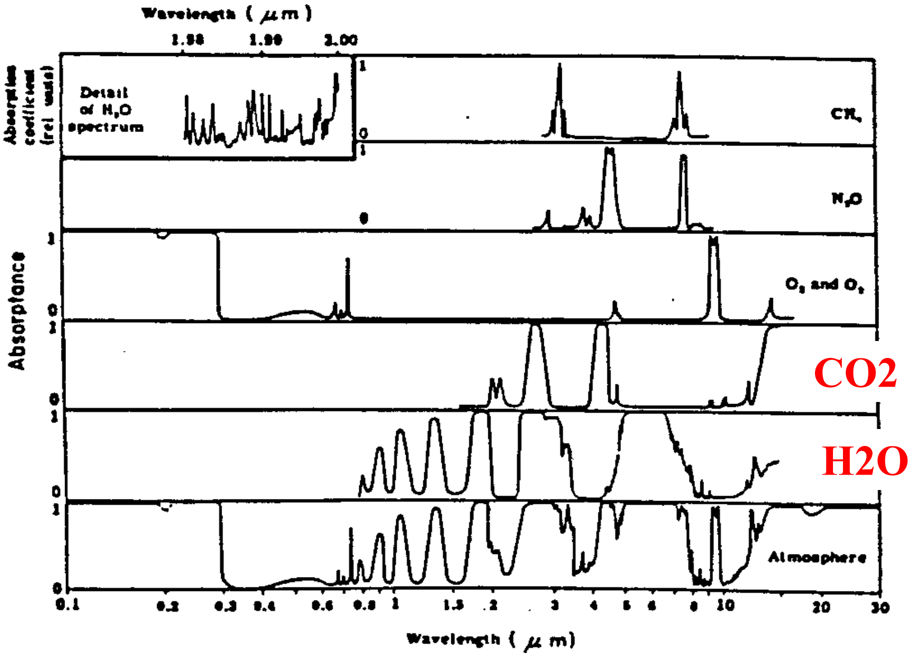
System Design for Oxy Retrofit

Oxy-Wet Case



The “practical” system
The recycle stream contains H2O
O2 aspects – supply, burner, product-flue

CCSD



Absorption/emission spectra for triatomic gases

Differences in radiating gases between air and oxy-fuel

Factor	Air firing	Oxy-fuel	Implications for oxy-fuel
CO2 + H2O	0.3	0.9	Higher emissivity
H2O / CO2	1	0.1, dry recycle 0.3, wet recycle 0.8, wet recycle, lignite	Emissivity of large furnaces cannot be estimated by standard Hottel charts, so band models must be used

CCSD

Objectives for furnace design

Thermal performance →

a. similar flame temperatures, giving ~ 30% O2 thru burner ;

b. similar furnace and convection pass heat transfer and similar or better combustion

CCSD

Oxy-Retrofit analysis

BASIS

- Achieve similar 'heat absorbed' (**Q**) to boiler tubes as the air case = f (Oxygen at burner inlet), using Hottel well-mixed furnace
- Achieve similar O_2 concentration in the flue gas as the air case = f(% XS air)

DETERMINE

- XS O2, defined here as %XS over O2 supply/O2 to burn the coal

ASSUME

- No air leakage

CCSD

Furnaces considered

1. **F-A : Pilot Scale Test furnace**
2. **F-B : Retrofit demonstration scale (30 MWe)**
3. **F-C : Large Scale (420 MWe)**

CCSD

Furnace Efficiency and Flame Temperature

The Hottel well-mixed model assumes:

➔ **Flame temperature = Flue gas exit temperature**

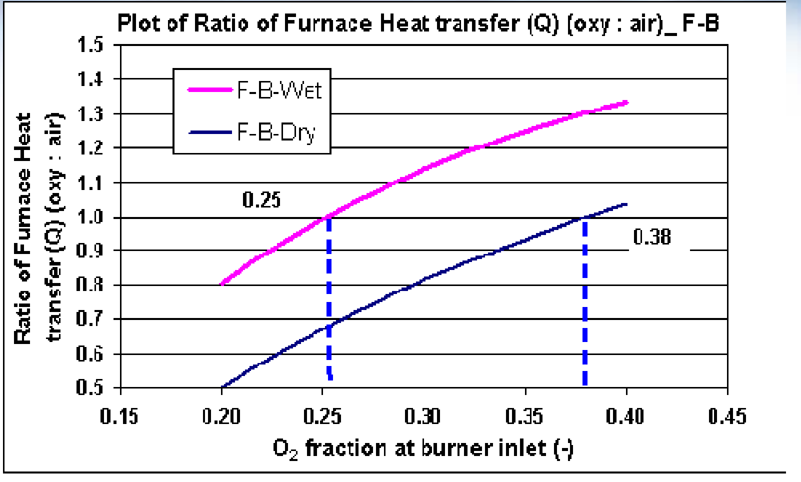
➔ **Sensible heat of coal + gas + specific energy of fuel = H_f = Heat absorbed by furnace + sensible heat in flue gases at flame temperature**

➔ **Furnace η = Heat absorbed by furnace / H_f**

CCSD

Retrofit - Oxygen at burner inlet for F-B

Plot for achieving similar boiler heat transfer (Q) as the air case



Basis: same oxygen concentration in flue

CCSD

RESULTS for Furnace F-B

for achieving similar boiler heat transfer (Q) as the air case

Cases	Air	Oxy-Dry	Oxy-Wet
% XS Air/ Oxygen	20	3.5	4.6
O_2 fraction at burner inlet	0.21	0.38	0.25
O_2 fraction in flue gas	0.033	0.033	0.033
Adiabatic flame temperature (AFT) °K	2200	2359	2040.7
Gas Temperature (°K)	1432	1364	1348
Recycle Ratio	-	1.36	2.55
Emissivity (Gas)	0.36	0.47	0.58
Emissivity (combined)	0.50	0.65	0.70
Heat associated with fuel/ m^2 of surface area	235.3	198.3	240.7
Heat absorbed /m^2 of surface area (kW/m^2)	94.93	95.7	95.6

CCSD

Estimated differences in FEGT, compared to air firing oxy-fuel temperatures are lower

	Oxy-Dry	Oxy-Wet
Furnace	dT (°K)	dT (°K)
F-A	36.7	49.9
F-B	68.1	84.3
F-C	40.8	44.4

CCSD

Other identified characteristics of oxyfuel retrofit

Flue gas volume is reduced, combustion time increased

Flue gas temperature reduced, ie suited to low AFT coals

CCSD

Convective pass evaluation

Heat transfer equations -

$$Q = m\,Cp\,(T_{C,IN} - T_{C,OUT})$$

$$Nu = 0.26\,(\mathrm{Re})^{0.6}\,(\mathrm{Pr})^{0.3}$$

Where, $Nu = \frac{hD}{K}, \mathrm{Re} = \frac{D\,u\,\rho}{\mu}, \mathrm{Pr} = \frac{C_P\,\mu}{K}$

Main impacts in oxyfuel -

Gas heat capacity and density increased, with reduction in mass flows and in gas velocity

CCSD

Convection pass heat transfer predicted

Table 12: Convective heat transfer results for air, oxy-dry and oxy-wet

	Air Case	Oxy-Dry	Oxy-Wet
Flue gas entering convective pass (°K)	1432	1365	1348
Velocity of flue gas entering convective pass (m/s)	9.8	5.0	7.5
Flue gas temperature leaving the convection pass (°K) and entering economizer	700	547 (iteration)	653 (iteration)
Overall Heat Transfer coefficient (W/m^2.k)	46.4	39.4	48.9
% Increase in convective heat transfer	-	-15.1 %	5.4 %

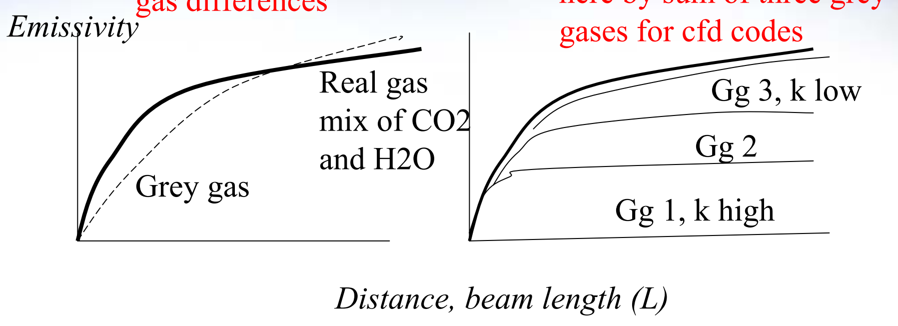
Notes:

Flue gas velocity calculated for air firing, scaled for oxy-cases

Tube area is not known, therefore flue gas temperature leaving convection pass set at 700K for air firing to establish area required, set at this value for oxy-cases

CCSD

Cfd furnace modelling: the difference between real gas (mixture of CO2 and H2O) and grey gas



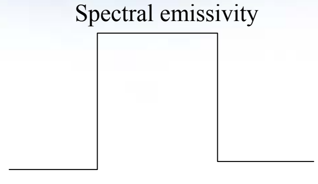
For grey gas, emissivity = 1 - exp (-kL), k – absorption coefficient (m-1)

Real gas emissivity (Hottel) charts have CO2/H2O band overlap corrections that do not apply for oxyfuel furnaces of Callide size, therefore band models must be used

CCSD

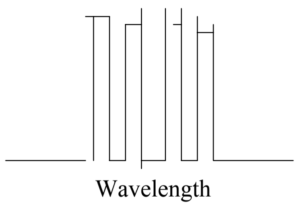
e=eC+cH-del, and and models account for del, the C/H band overlap

Wide band model – represents bands as top hat shape, covering the band width



OK for low concentrations x beam length

Narrow band model – represents each band as series of lines, within the bands



May be needed for high concentrations x path length, where the correction is greater

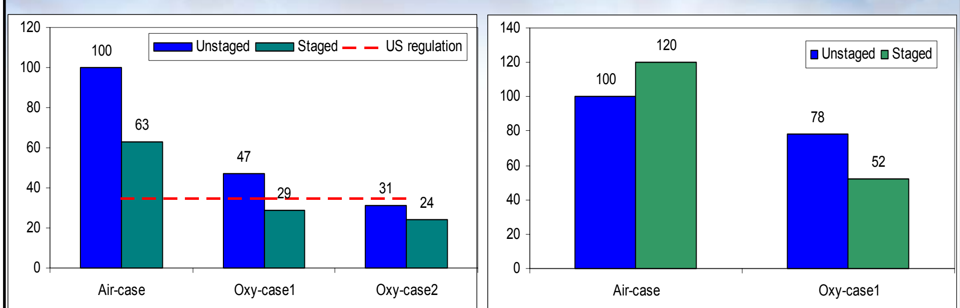
CCSD

Pilot-scale testing – commonly has reported heat transfer evaluations, combustion and NOx

……… Several reported studies give comparisons between oxy-fuel and air combustion, for the same coals

CCSD

Several pilot-scale results confirm NOx reduction and burnout improvement …..



(a) NOx 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.

CCSD

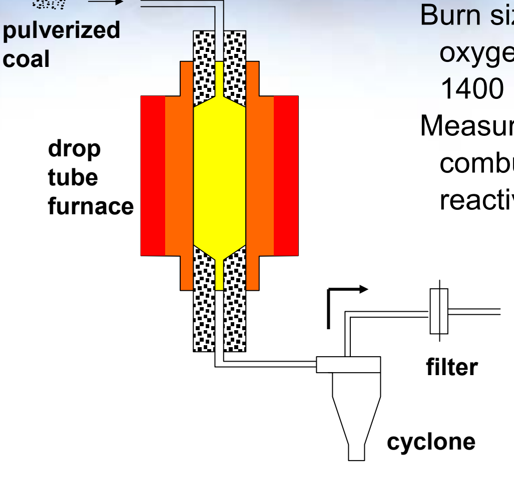
Laboratory coal reactivity studies

Lisa Elliott, Raj Rupta, Sameer Khare, Renu Rathnam

….. focussing on volatile yield and char reactivity required for cfd codes

CCSD

Experiments in Astro drop tube furnace



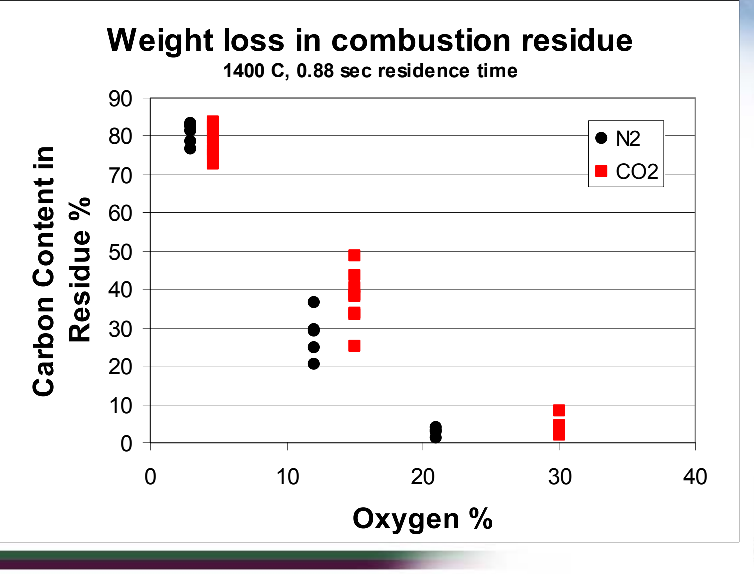
Burn size cut of coal in varying oxygen concentrations in DTF at 1400 °C,

Measure carbon burnout from combustion residue to determine reactivity (conversion)

The University of Newcastle

CCSD

Results indicate there can be differences in burn-out in O2-N2 and O2-CO2



CCSD

V* and Q factors (=V*/VM) measurements (ad basis)

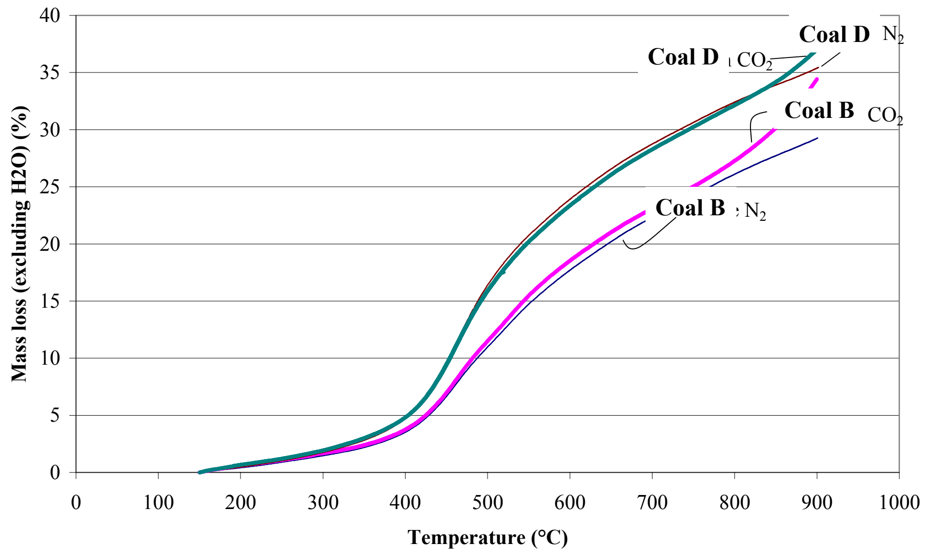
	Coal A	Coal B	Coal C	Coal D
Proximate Analysis Volatile Matter (a.d.)	25.6	24.5	40.5	33.8
N_2 V*	36.7	30.9	52.4	53.5
Q factor	1.43	1.26	1.29	1.58
CO_2 V*	43.3	32.2	55.3	66.2
Q factor	1.69	1.32	1.36	1.96

Note: for +63 - 90um fraction

Note: estimates higher in CO2 environment

The University of Newcastle CCSD

TGA pyrolysis measurements in N2 and CO2 to determine significance of C-CO2 rxn



CCSD

Combustion for the VEGA code: first order combustion reaction rate for char (1)

First order reaction rate (n=1) assumes the reaction of carbon with oxygen to form CO on the char surface

Combustion rate q - mass of carbon per unit ***external*** surface area - depends on diffusivity (oxygen to surface):

$$q = k_D\left(p_g - p_s\right)$$

And on coal reactivity:

$$q = k_R p_s^n$$

The University of Newcastle

CCSD

Combustion for the VEGA code: first order combustion reaction rate for char (2)

For first order, n=1, and equating the two combustion rates results in:

$$q = \frac{p_g}{\left(\frac{1}{k_R} + \frac{1}{k_D}\right)}$$

k_D can be obtained from literature,
k_R can be calculated from:

$$k_R = Ae^{-\frac{\Delta E}{RT_p}}$$

The University of Newcastle

CCSD

Equations for half and partial order

For n= ½, $q = k_R p_s^{1/2}$, and

$$q = \frac{k_R}{2}\left[\left(\left(\frac{k_R}{k_D}\right)^2 + 4p_g\right)^{1/2} - \frac{k_R}{k_D}\right]$$

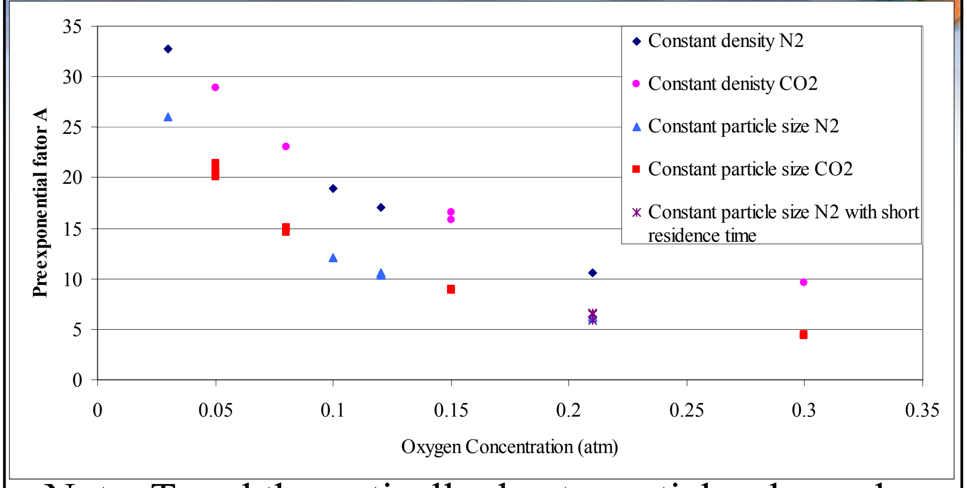
Alternatively analyze as first order with the apparent A then becoming

$$A\left(pO_2\right)^{n-1}$$

… that is, plot A ~ pO2, if n<1 then A will decrease

CCSD

Char reactivity pre-exponential constant estimates



Note: Trend theoretically due to partial order and and/or reduction of reactivity with burnout

CCSD

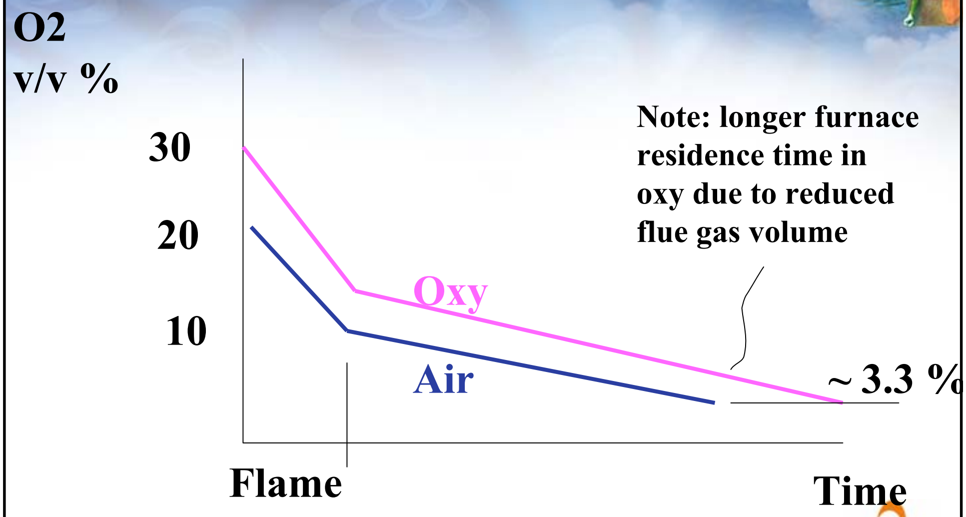
Fits for A based on first order

~ n-1

	Constant particle size	Constant density
N_2	$A = 2.04(pO_2)^{-0.76}$ $R^2 = 0.98$	$A = 4.90(pO_2)^{-0.56}$ $R^2 = 0.97$
CO_2	$A = 1.66(pO_2)^{-0.86}$ $R^2 = 0.99$	$A = 4.87(pO_2)^{-0.61}$ $R^2 = 0.99$

CCSD

Do we expect better combustion in oxyfuel? ….. Illustrative oxygen paths thru' furnace



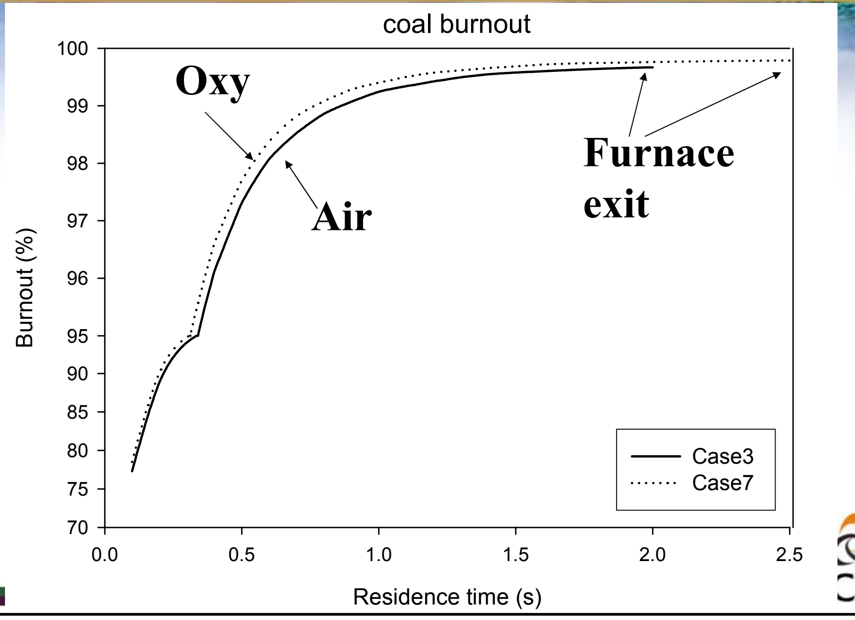
CCSD

Factors determining coal char burnout when furnace heat transfer is matched for a retrofit

Operational factor	Air fired	Oxyfuel		***Equivalent factor determining coal char burnout***	Air fired	Change, compared to air firing	
		Wet recycle	Dry recycle			Wet recycle	Dry recycle
Oxygen through burners, % v/v	21%	26%	38%	The ***oxygen partial pressure*** experienced by burning coal char is higher in oxyfuel			
Furnace flue gas volumetric flow, expressed as kmol/hr	56630	43950	29870	***Coal residence time*** in furnace is higher in oxyfuel, s	2.05	2.51	3.80
Change in adiabatic flame temperature. °C	-	-60°C	+160°C	The ***gas temperature*** experienced by coal char will differ in oxyfuel, being lower with wet recycle			
Change in furnace exit gas temperature (FEGT), °C	-	-84 °C	-68 °C				

CCSD

Burnout comparisons at gas temperature of 1400 C



NOx

….. many pilot-scale studies report reductions with oxy-fuel, and Okazaki's research explains the mechanisms

NOx Reduction - Decrease of Conversion Ratio from Fuel-N to NOx

Summary of CR^* values for O_2/CO_2 coal combustion

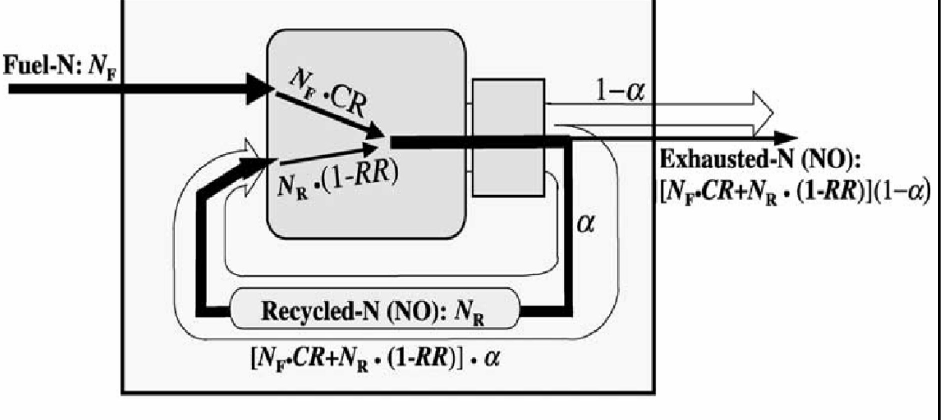
λ (oxygen-fuel stoichiometric ratio)	0.7	1.0	1.2
NO concentration in exhaust gas	1130 ppm	1710 ppm	1490 ppm
CR^*	0.05	0.12	0.13
Ratio of CR^* to that of air combustion	17 %	25 %	26 %

CR^*: conversion ratio from fuel-N to exhausted NO

$$\text{Ratio of } CR^* \text{ to that of air combustion} = \frac{CR^* \text{ in } O_2/CO_2 \text{ coal combustion}}{CR^* \text{ in conventional coal combustion in air}}$$

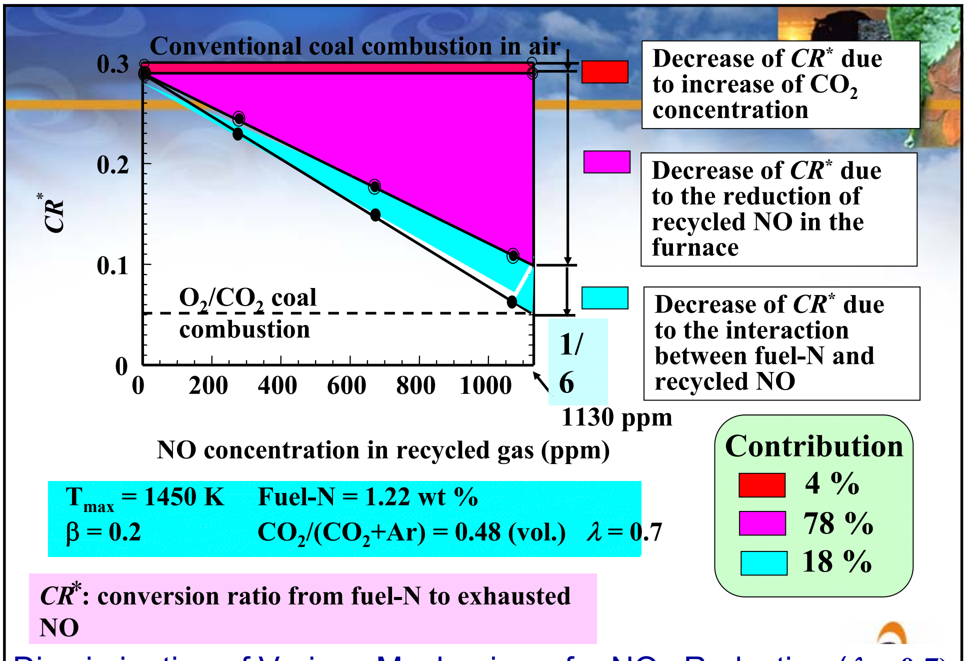
CCSD

NOx Reduction Mechanism

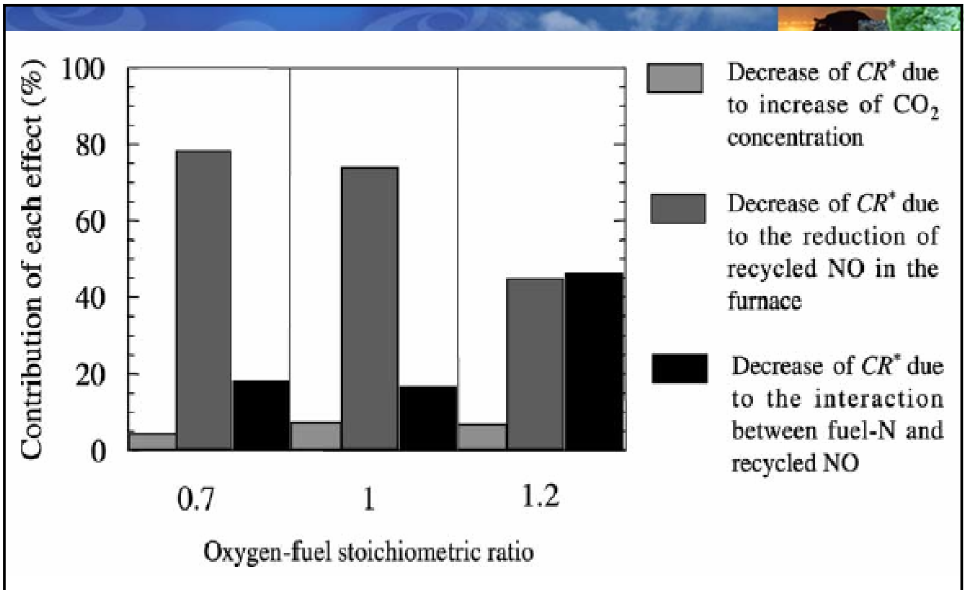


$$N_R = \alpha \cdot N_F \cdot CR / [1 - \alpha (1\text{-}RR)]$$

CCSD



Discrimination of Various Mechanisms for NOx Reduction (λ = 0.7)

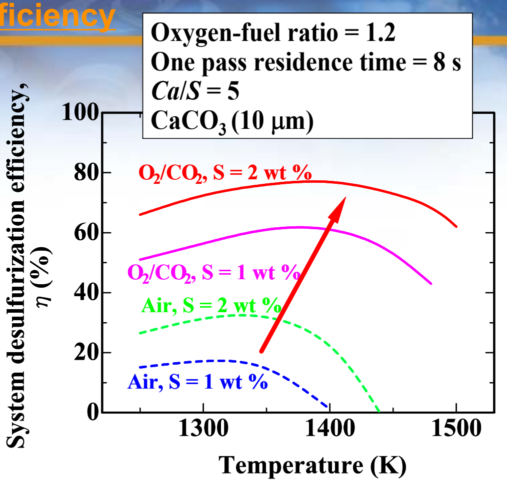


Change of NOx Reduction Mechanisms with λ (oxygen-fuel stoichiometric ratio)

SOx

….. and natural reduction by calcium in ash and additions for in-furnace desulfuration

Drastic Enhancement of In-furnace Desulfurization Efficiency



η at S = 1 wt %

six times higher

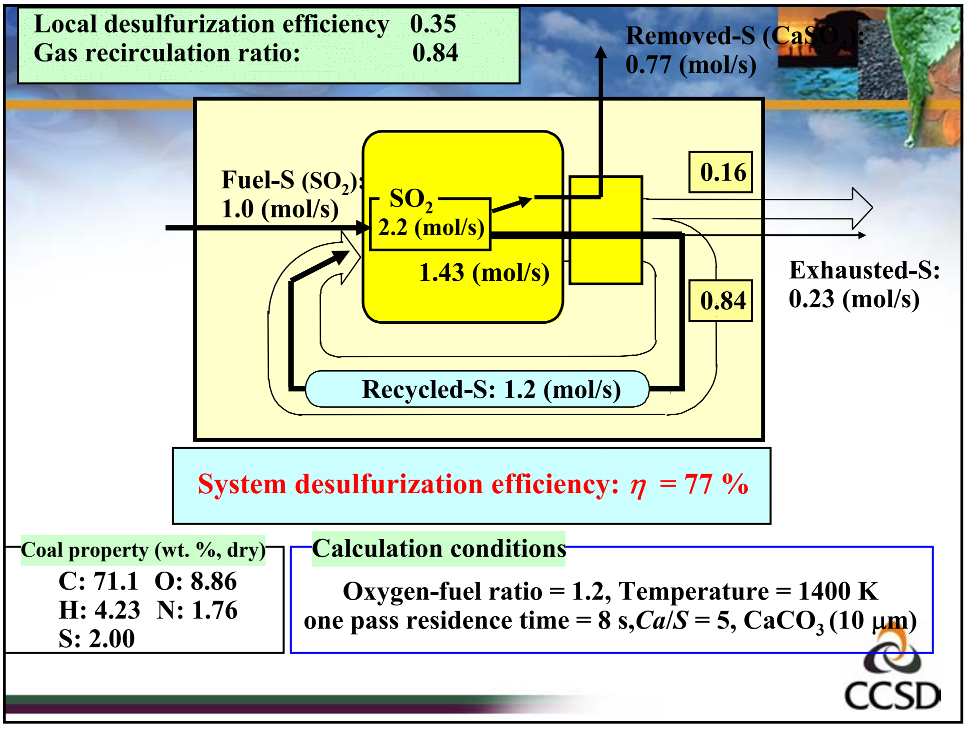
In-furnace desulfurizatioin at high temperature

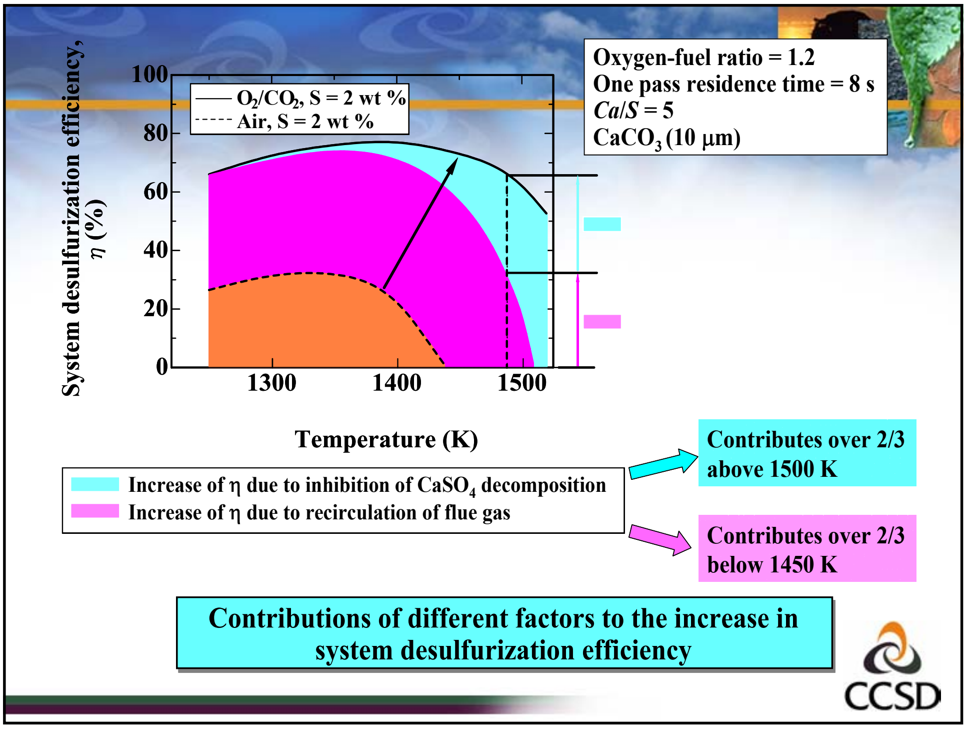
Air: impossible

O_2/CO_2: can be realized

η in O_2/CO_2 ➡ about four times higher ➡ high in a wide temperature range

Effect of temperature on system desulfurization efficiency


Local desulfurization efficiency 0.35
Gas recirculation ratio: 0.84
Removed-S (CaSO4):
0.77 (mol/s)
Fuel-S (SO2):
1.0 (mol/s)
SO2
2.2 (mol/s)
1.43 (mol/s)
0.16
0.84
Exhausted-S:
0.23 (mol/s)
Recycled-S: 1.2 (mol/s)
System desulfurization efficiency: η = 77 %
Coal property (wt. %, dry)
C: 71.1 O: 8.86
H: 4.23 N: 1.76
S: 2.00
Calculation conditions
Oxygen-fuel ratio = 1.2, Temperature = 1400 K
one pass residence time = 8 s, Ca/S = 5, CaCO3 (10 μm)
CCSD


System desulfurization efficiency, η (%)
100
80
60
40
20
0
O2/CO2, S = 2 wt %
Air, S = 2 wt %
Oxygen-fuel ratio = 1.2
One pass residence time = 8 s
Ca/S = 5
CaCO3 (10 μm)
1300
1400
1500
Temperature (K)
Increase of η due to inhibition of CaSO4 decomposition
Increase of η due to recirculation of flue gas
Contributes over 2/3 above 1500 K
Contributes over 2/3 below 1450 K
Contributions of different factors to the increase in system desulfurization efficiency
CCSD

Gas quality impacts

….. where theoretical differences are expected and some results have been reported, but where results have not been released

CCSD

Listing of fundamental questions

Are trace element emissions, particularly Hg, reduced and if so, how?

Are corrosive gases, SO3 and COS, changed. If so, are low-S fuels required?

What is the CO2 purity required for compression, and therefore allowable air leakage. Is equilibrium data with impurities required ?

CCSD

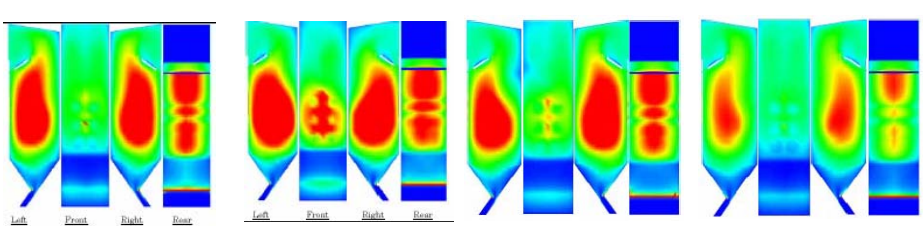
Mathematical modelling

…. which has yet to be used to any great extent

CCSD

Final comment: Cfd furnace simulation is the tool whereby fundamental research can be applied

	Air-case	Oxy-case1	Oxy-case2	Oxy-case3
Total gas flow rate	142t/h	117t/h	140t/h	170t/h
O_2 content	21%	30.2%	26.0%	1.7%
(WB O_2 content	21%	50%	40%	30%)



Air-case Oxy-case1 Oxy-case2 Oxy-case3

CCSD

Final comments

Several differences observed are ‘system’ effects due to the recycle stream ……

…..the way forward is logically to combine laboratory studies of fundamental factors with pilot-scale studies which simulate ‘system’ effects

CCSD

Inaugural Workshop

International Oxy-Combustion Research Network

Vattenfall Europe Mining and Generation AG Head Office
Cottbus, Germany

29th and 30th November 2005

PRESENTATION - 03

Technology Choice and Benchmarking Studies

by:

Prof. Lars Stromberg
Vattenfall AB, Sweden

This page is intentionally left blank

IEA GHG Workshop on Oxyfuel
Technology choice - Benchmarking

Cottbus 29-30th November 2005
Cottbus, Germany

Lars Strömberg
Vattenfall AB
Corporate Strategies
Berlin / Stockholm

VATTENFALL

Schwarze Pumpe power plant

2

VATTENFALL

Reduction of CO_2

Why oxyfuel technology ????

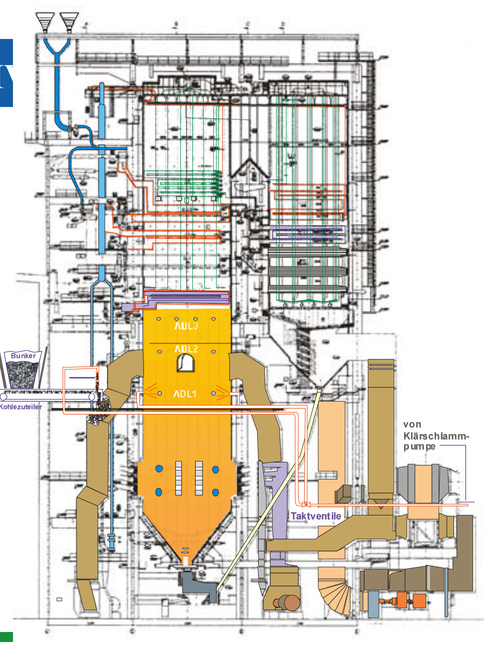
VATTENFALL

Boxberg I

Why Oxy-fuel technology ?

We work with all three (four) technologies, but:

- Oxyfuel technology is the technology giving lowest costs at present
- It is suitable for coal and have relatively little development work left
- We can build on our good experience with present PF technology



VATTENFALL

Power Plant Lippendorf

VATTENFALL

CO_2 free power plant

Benchmarking

VATTENFALL

CO_2 free power plant - Why different costs ?

- Numerous different views on costs for technologies exist.
- Recent IPCC report did not make it better
  - The IPCC report is based on reviewed papers published in Journals, not conference papers or real figures from real cases
  - The IPCC report is obviously wrong in the tables stating present generation cost of electricity
- Several of the IEA papers are of similar origin, or made on contract

VATTENFALL

CO_2 free power plant - Why different costs II

- Academic papers report as they should. – What they find in litterature, or in the lab, even if it sometimes is meaningless,
  - For example, giving an interval from 7 – 80 €/ton. Correct probably, but misleading
- The costs are treated differently in different papers.
  - For example, transport is considered costing up to 50 €/ton CO_2. We know that it should cost about 3,7 €/ton from Scwarze Pumpe to Schweinrich. We often talk about the level 5 €/ton of CO_2 for transport and 2 €ton for storage for a large case.
  - Capital, O&M and Fuel costs differ largely
  - The way calculations are made differ significantly
- Costs for a small unit is much higher than for a large
  - There exist a considerable volume dependence. We often talk about a power unit of up to 750 MW. There is no sense to capture CO_2 from a small plant - It is too expensive. Transport costs for the pilot is 21 €/ton CO_2
- Cost are different for a Coal and a Gasfired unit, even with similar technology
  - If costs are expressed as €/ton CO_2, reduction from gas is more expensive due to the higher gas price and the lower amount of CO_2 produced
  - A large part of the cost is due to that it costs energy to separate the CO_2. Energy is taken from the plant. This energy is more expensive when fuel costs are higher. 15 €/ton for a coal plant is eqiuivalent to 50 €/ton for a gas fired unit

VATTENFALL

CO_2 free power plant - Why different costs III

- Many data are biased. Almost all papers want to show something.
  - Many Norwegian papers seems to push for gas
  - American and French papers appears as they want to show that it is impossible due to economic reasons
  - Results seems to be adjusted to a general “political” view in several countries.
- Many reports are based on marketing of products
  - For example, a market leading gas turbine manufacturer comes to the conclusion that a plant including a gas turbine is the most beneficial. OK it’s their job.
  - A market leading Fluidized bed manufacturer comes to the conclusion that a CFB is more beneficial than any other boiler technology.
  - Leading companies working with gasification not surprisingly comes to the conclusion that a gasifier is the best and least expensive.- Even at present, which we all know is not correct. This is also expressed by the IPCC report !!
- Some American papers have a different way of handling the loss of energy output.
  - They consider it bought from the grid at some price. For a power plant this is not adequate. It is taken from the own plant and increase the cost of production for the actual delivered energy
- Many studies are considering a retrofit situation.
  - Retrofitting an existing plant is more expensive than building a specially designed new plant
  - Efficiency difference is 2 – 4 %-units.

VATTENFALL

CO_2 free power plant

Benchmarking 1

2001 - 4

VATTENFALL

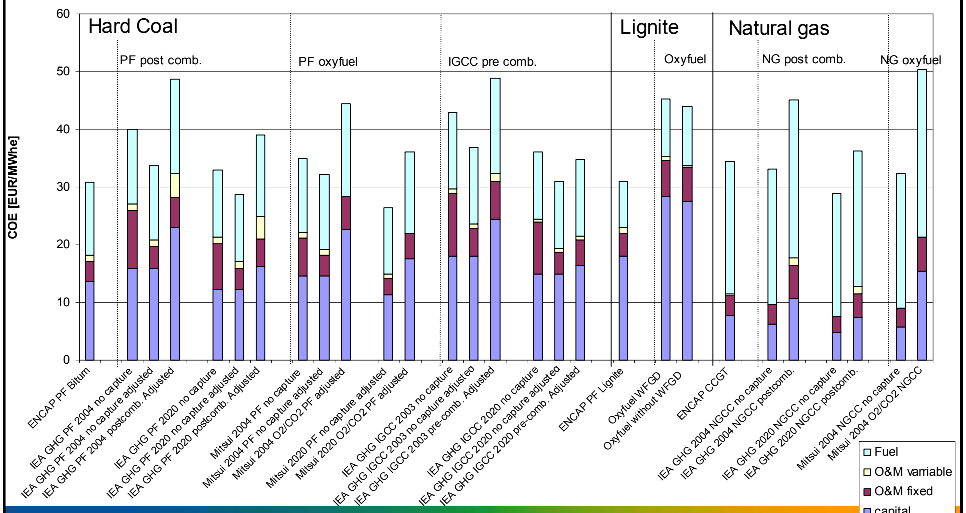
Data for the 2004 study

- Data for the capture alternatives and reference plants from recent studies made by IEA GHG
  - IGCC options from study 2003
  - Post-combustion options for bituminous coal and natural gas from study from 2004
  - Oxyfuel options for bituminous coal (without FGD) and natural gas from study 2004, costs updated 2005
- Data for reference plants from ENCAP
- Oxyfuel lignite
  - Oxyfuel options for lignite, with and without FGD, based on 1000 MWgross lignite fired ENCAP reference plant with atm. lignite drier and 1st “base” oxyfuel concept by VF (within ENCAP SP3).
  - Cost changes compared to reference plant based on IEAGHG oxyfuel study 2004 and other data presently available. The oxyfuel case will be further optimised – work ongoing
- Interest rate 7% real, 25 years, 7500 hrs/year
- Bit. Coal 5.7 €/MWh, Lignite 3.9 €/MWh, Gas 13 EUR/MWh

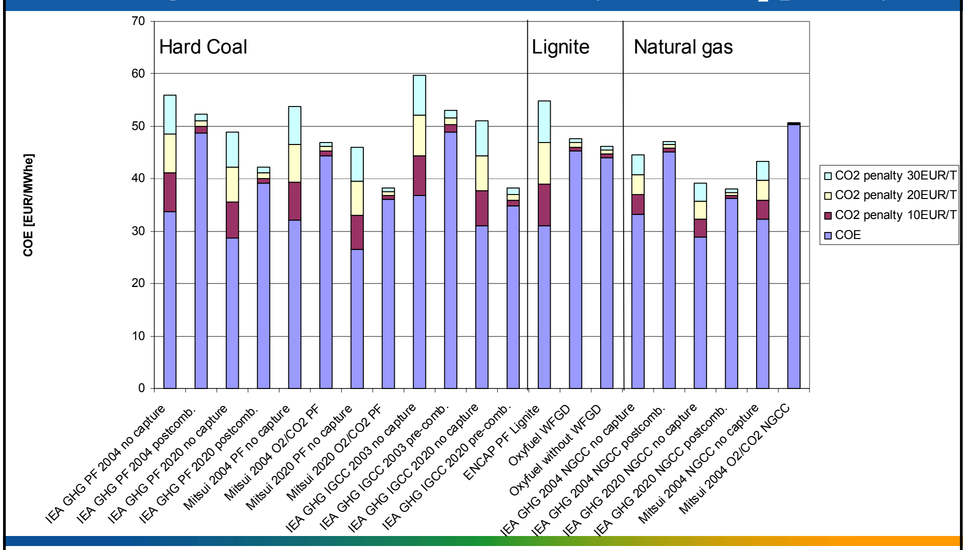
Adjustments

- It was noted that the IEA commissioned studies generally presented very high fixed O&M costs (insurance and taxes specifically) on the coal fired plants compared to data from ENCAP partners and some of our own internal information
  - IEA data adjusted to the same level as in the ENCAP guidelines (25.2 €/kWe gross for all PF coal cases, 2.6% of total investment in the IGCC cases)
  - Capture cases were adjusted so that the fixed O&M (% of investment) is kept constant between reference and capture cases
- After this adjustment, the coal fired reference cases present total COE at approximately the same level which indicates that the cases uses similar basic assumptions
- In addition, natural gas and coal reference cases show total COEs that are in the same range – seems to agree with actual situation today considering the variations in fuel price
- Reference IGCC today is not competitive with PF – also agrees with actual situation

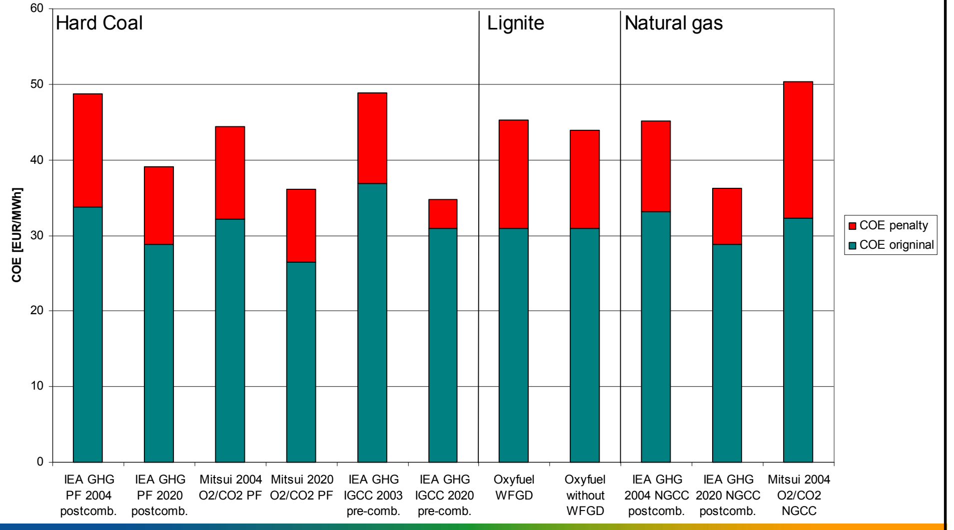
Cost of electricity with and without CO_2 capture



Total generation cost of electricity with CO_2 penalty



Generation cost with and without CO_2 capture



VATTENFALL

CO_2 free power plant

Gasification ?????

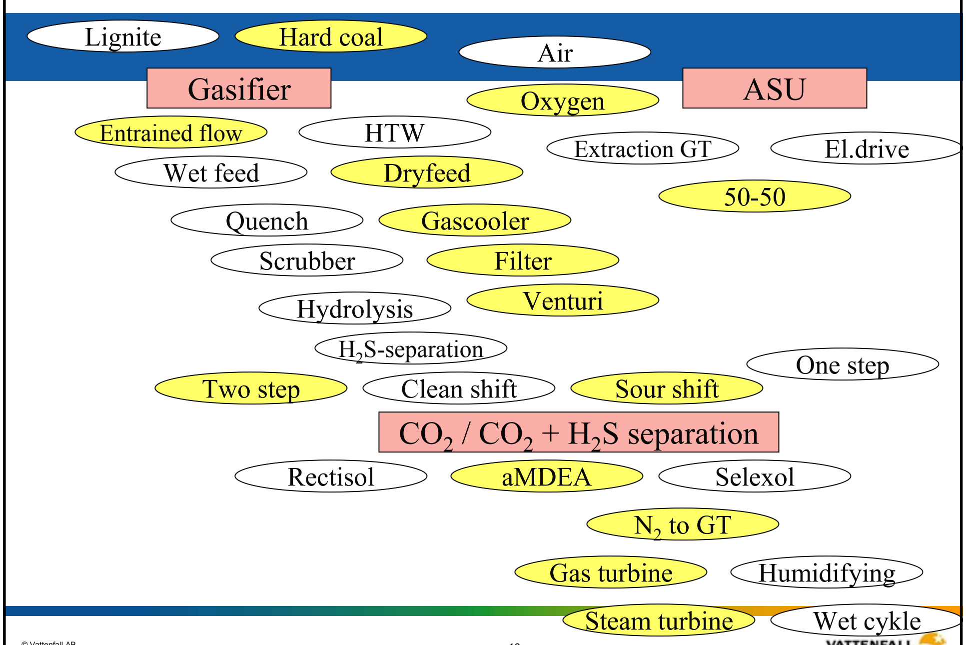
VATTENFALL

Techno-economical study IGCC

- The objective is to study and compare the physical washing step for capturing of CO_2 for IGCC.
- To formulate a preferred concept on IGCC with CO_2 capture.
- To follow up the ENCAP SP2 and COORETEC activities on IGCC and CO_2 capture.

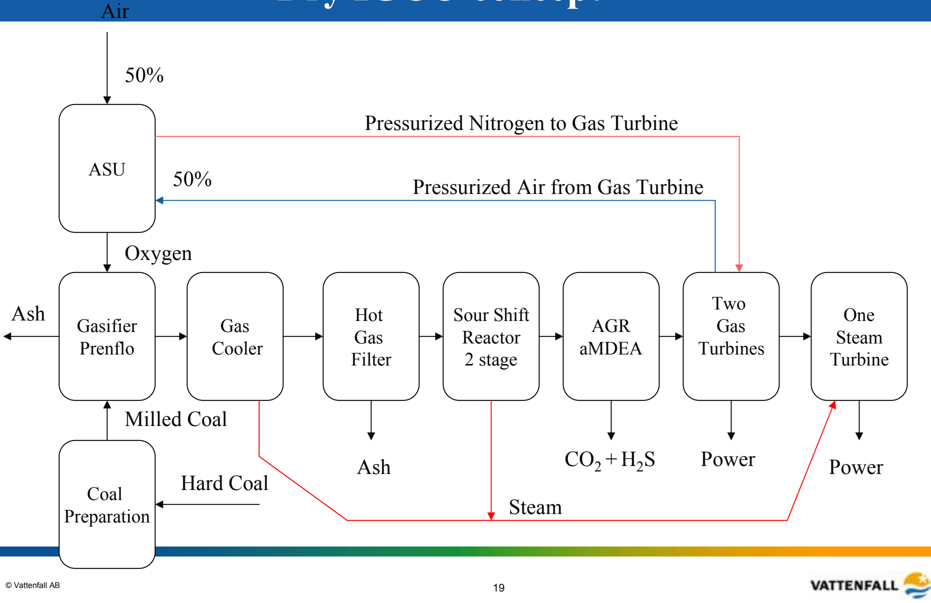
  VATTENFALL

IGCC technology and process choices



  VATTENFALL

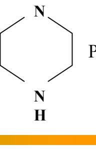
Dry IGCC-concept



VATTENFALL

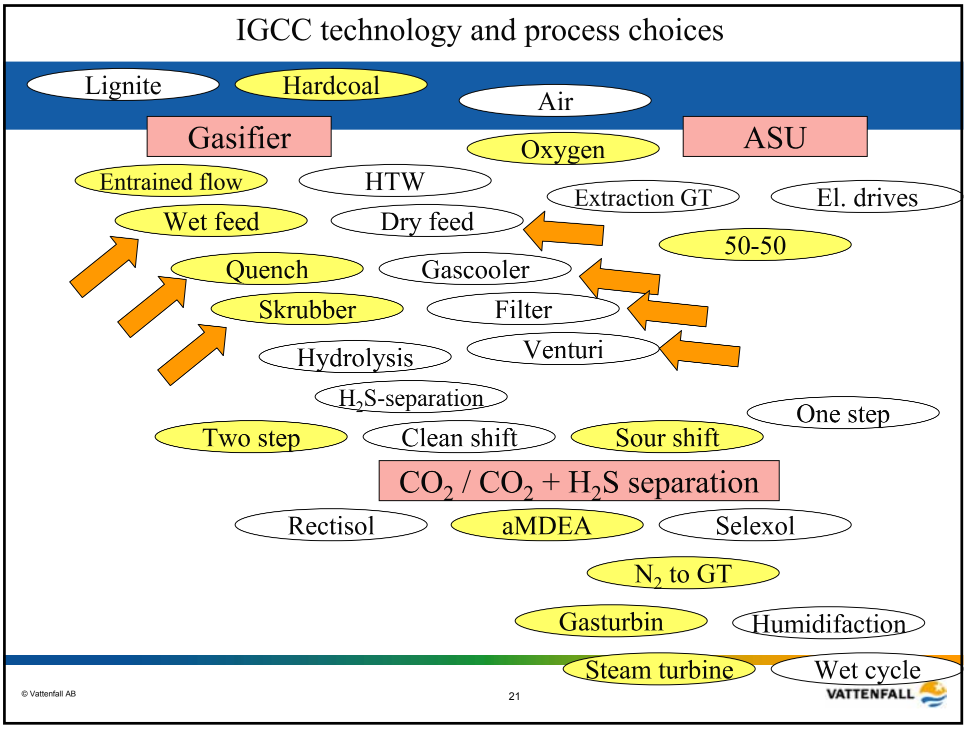
Choice of av Acid gas removal

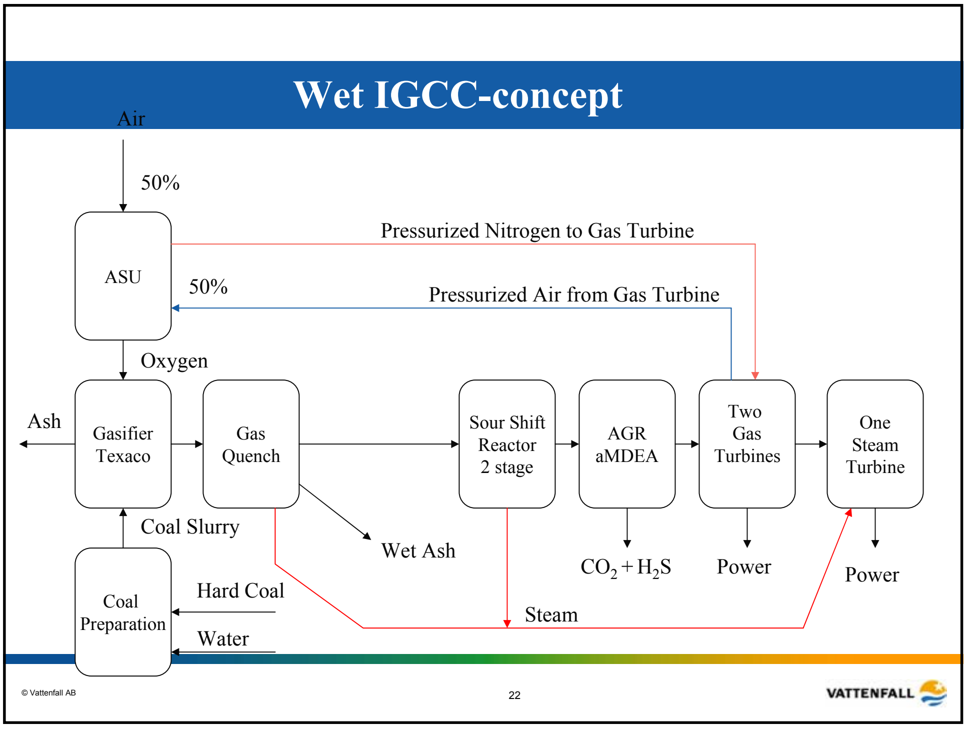
- Acid gases can be washed out with alcohol, glycole, amine, etc.
- Rectisol, aMDEA and Selexol are possible processes.
- Physical solvents have lower regeneration need than chemical solvents.
- Rectisol and Selexol uses a physical solution of the acid gases
- aMDEA is a Physical.chemical solvent
- Rectisol was not chosen, due to that it was used in ENCAP SP2 and a too large electricty need for regeneration
- aMDEA was chosen because IEA PH4/19 rreported a lower loss of hydrogen, lower loss of solvents, lower energy need for regeneration and we might get a good set of data from BASF and for it is used in many reference plants

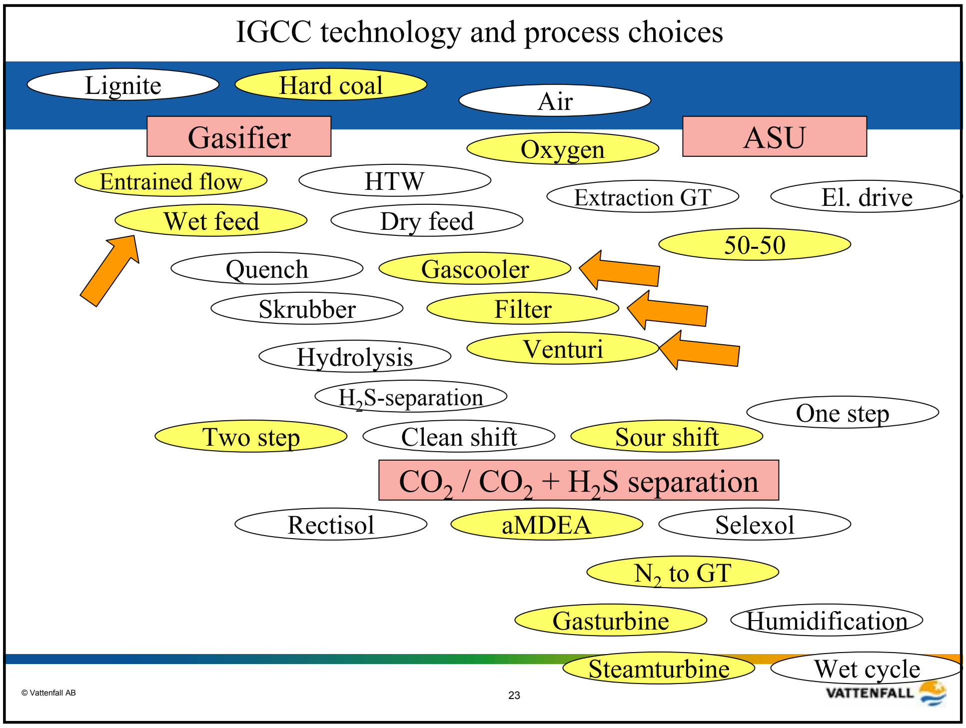


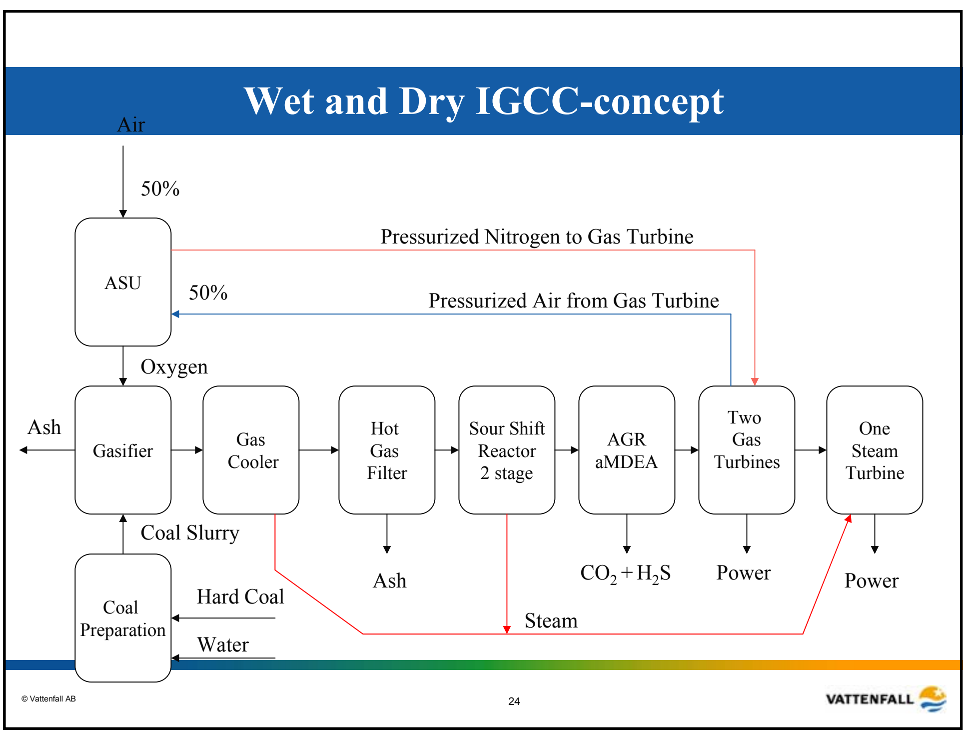
Piperazin

VATTENFALL

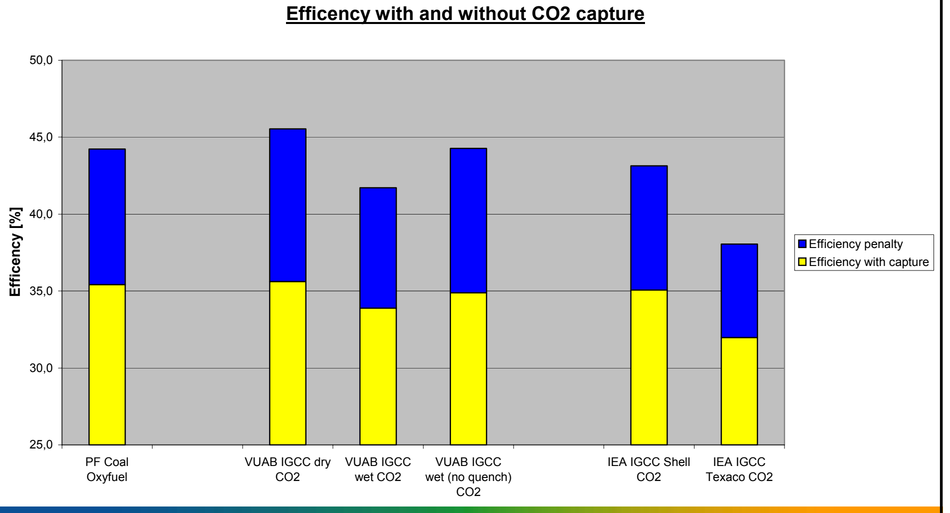

IGCC technology and process choices
Lignite
Hardcoal
Air
Gasifier
Oxygen
ASU
Entrained flow
HTW
Extraction GT
El. drives
Wet feed
Dry feed
50-50
Quench
Gascooler
Skrubber
Filter
Hydrolysis
Venturi
H_2S-separation
One step
Two step
Clean shift
Sour shift
CO_2 / $CO_2 + H_2S$ separation
Rectisol
aMDEA
Selexol
N_2 to GT
Gasturbin
Humidifaction
Steam turbine
Wet cycle
© Vattenfall AB
21
VATTENFALL


Wet IGCC-concept
Air
50%
ASU
Pressurized Nitrogen to Gas Turbine
50%
Pressurized Air from Gas Turbine
Oxygen
Ash
Gasifier Texaco
Gas Quench
Sour Shift Reactor 2 stage
AGR aMDEA
Two Gas Turbines
One Steam Turbine
Coal Slurry
Wet Ash
$CO_2 + H_2S$
Power
Power
Coal Preparation
Hard Coal
Water
Steam
© Vattenfall AB
22
VATTENFALL


IGCC technology and process choices
Lignite
Hard coal
Air
Gasifier
ASU
Oxygen
Entrained flow
HTW
Extraction GT
El. drive
Wet feed
Dry feed
50-50
Quench
Gascooler
Skrubber
Filter
Hydrolysis
Venturi
H2S-separation
One step
Two step
Clean shift
Sour shift
CO2 / CO2 + H2S separation
Rectisol
aMDEA
Selexol
N2 to GT
Gasturbine
Humidification
Steamturbine
Wet cycle
© Vattenfall AB
23
VATTENFALL


Wet and Dry IGCC-concept
Air
50%
ASU
Pressurized Nitrogen to Gas Turbine
50%
Pressurized Air from Gas Turbine
Oxygen
Ash
Gasifier
Gas Cooler
Hot Gas Filter
Sour Shift Reactor 2 stage
AGR aMDEA
Two Gas Turbines
One Steam Turbine
Coal Slurry
Ash
CO2 + H2S
Power
Power
Coal Preparation
Hard Coal
Water
Steam
© Vattenfall AB
24
VATTENFALL

Technical / economical evaluation



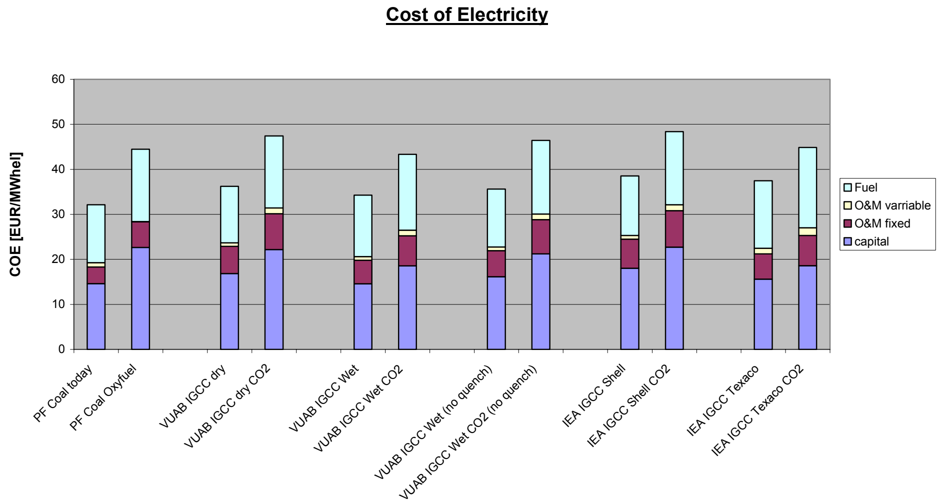
VATTENFALL

Economic assumptions for the COE calculations

- Dollar/Euro conversion rate = 1
- Fuel cost hard coal: 5,7 EUR/MWh_{fuel}
- Operating hours: 7500 h
- Intrest rate calculus: 7%
- Depretiation time: 25 years
- Fixed O&M cost: 3,5% of the investment in all IGCC cases (25,2 EUR/kW_{el} in the PF case)
- Variable O&M cost: different depending on if aMDEA or Selexol and with or without CO_2-capture
  - aMDEA w/o CO_2 separation = 0,7 EUR/MWh_{el} gross
  - aMDEA with CO_2 separation = 1,0 EUR/MWh_{el} gross
  - Selexol w/o CO_2 separation = 1,1 EUR/MWh_{el} gross
  - Selexol with CO_2 separation = 1,3 EUR/MWh_{el} gross
- The cost calculations are preliminary
- Investments costs for VUAB's IGCC alternative are based on scaled values from IEA's IGCC report. Costs for the ASU and the Power Island should be revised, as also the values for the gasifier in the wet/dry case.

VATTENFALL

Technical / economical evaluation



 27 VATTENFALL

CO_2 free power plant

Benchmarking 2
2005

”Incl. recent results Encap”

 28 VATTENFALL

Calculation basis

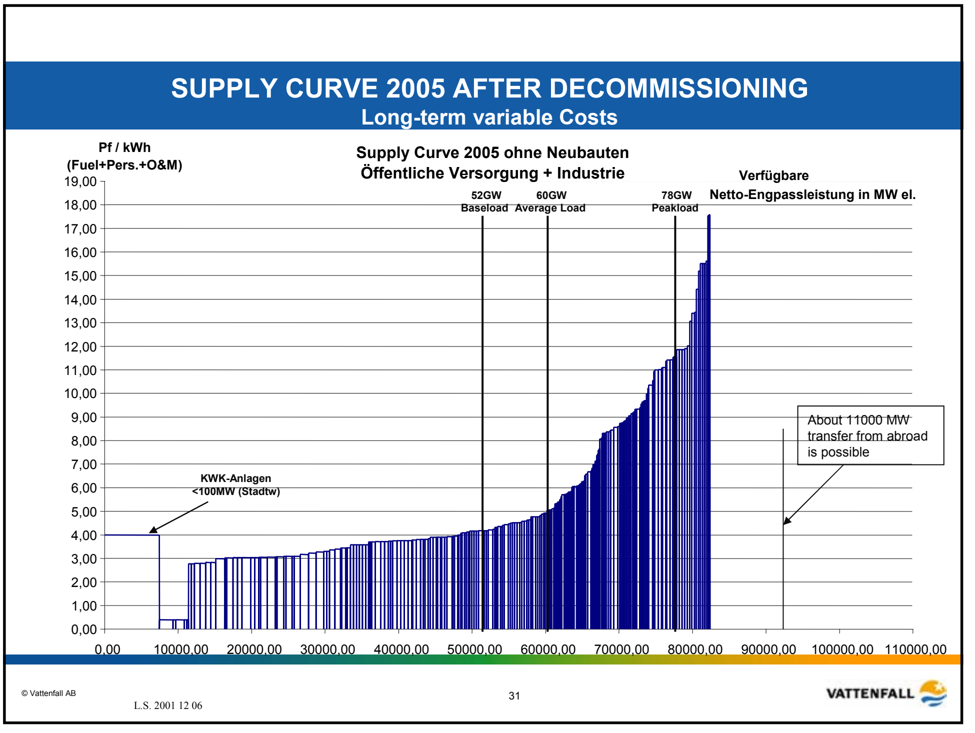
- Fuel Prices:
  - Bituminous Coal 5.7 €/MWh, (1,6 €/GJ)
  - Lignite 3.9 €/MWh, (1,1 €/GJ)
  - Natural Gas 13 EUR/MWh (3,5 €/GJ)
- Interest rate 7,5 % real
- Economic lifetime 25 years
- Annual operation 7500 hrs/year

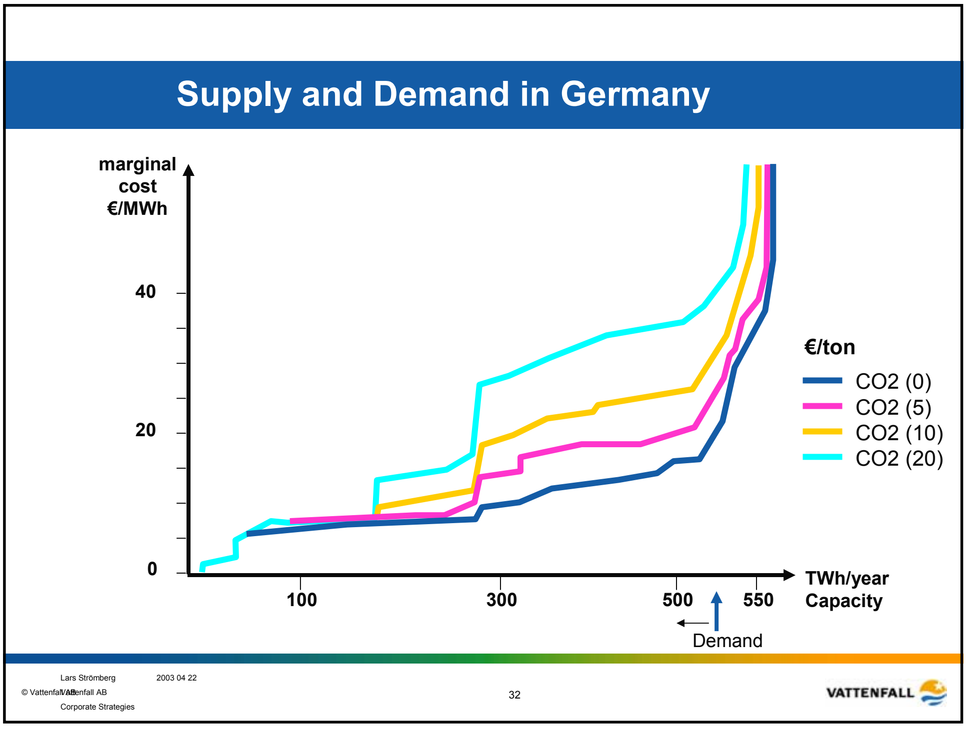
VATTENFALL

Calculation basis

- The calculations use one number for operating hours: 7500 hours.
- The problem is that operation time per year will be depending on
  - Variable cost – dispatch order.
  - Availability.
- Some units with high variable cost will not be operated during summer in northern Europe. (high gas prices ?)
- Vattenfalls existing ultra supercritical coal fired plants have a very high availability > 95 % including planned overhaul
- The cost of fuels is very uncertain, but coal more stable than gas. Lignite is cost based

VATTENFALL


SUPPLY CURVE 2005 AFTER DECOMMISSIONING
Long-term variable Costs
Pf / kWh
(Fuel+Pers.+O&M)
Supply Curve 2005 ohne Neubauten
Öffentliche Versorgung + Industrie
Verfügbare
Netto-Engpassleistung in MW el.
52GW Baseload
60GW Average Load
78GW Peakload
KWK-Anlagen
<100MW (Stadtw)
About 11000 MW transfer from abroad is possible
© Vattenfall AB
L.S. 2001 12 06
31
VATTENFALL

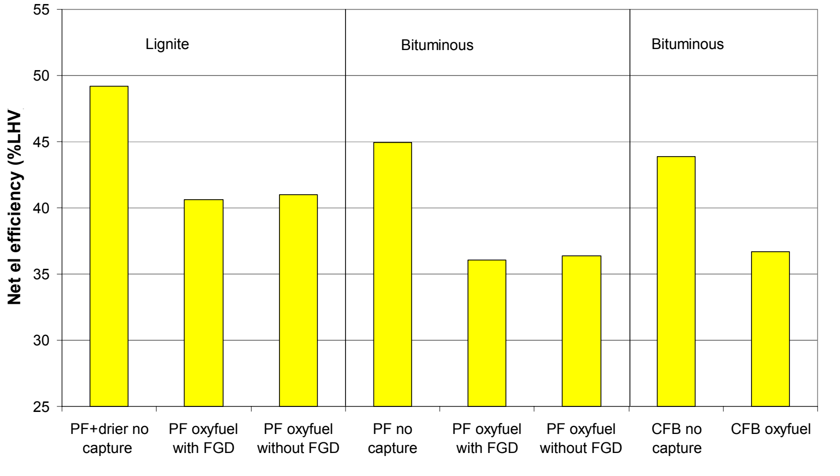

Supply and Demand in Germany
marginal cost €/MWh
40
20
0
100
300
500
550
TWh/year
Capacity
Demand
€/ton
CO2 (0)
CO2 (5)
CO2 (10)
CO2 (20)
Lars Strömberg
2003 04 22
© Vattenfall AB
Corporate Strategies
32
VATTENFALL

Benchmarking

Oxyfuel alternatives

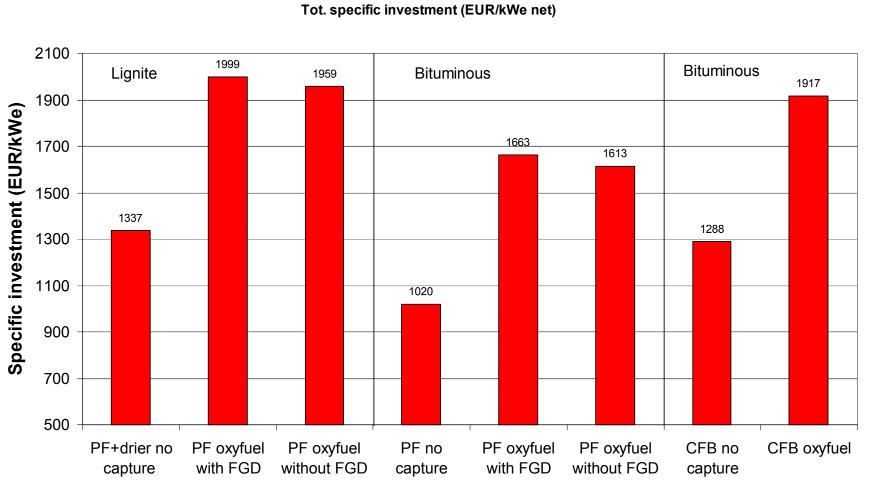
VATTENFALL

Net efficiencies (LHV) for PF and CFB cases



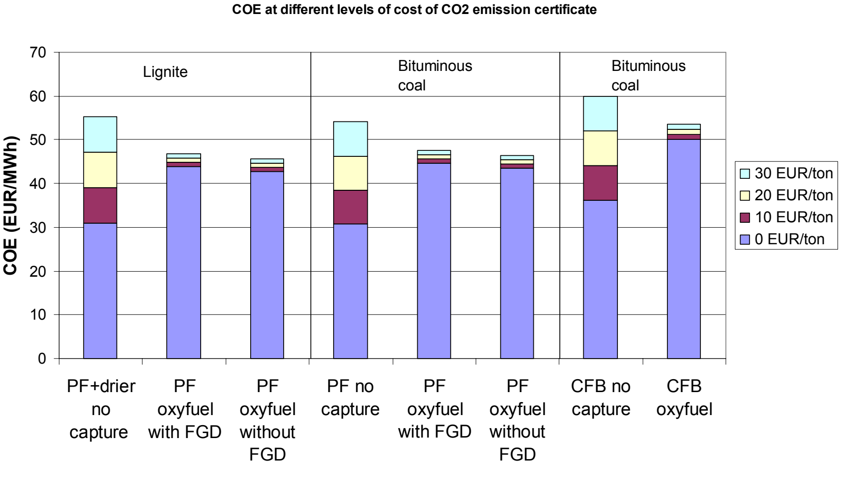
VATTENFALL

Specific investments for PF and CFB alternatives



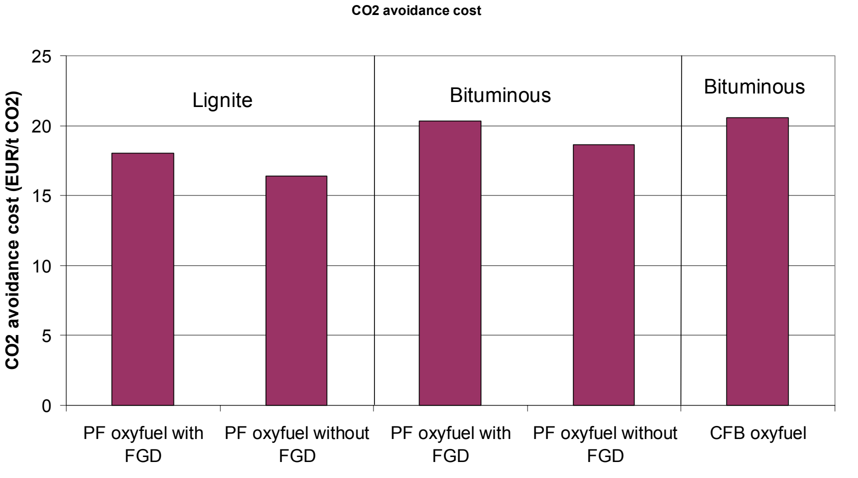
VATTENFALL

Cost of electricity incl. CO2 penalty



VATTENFALL

Avoidance costs for oxyfuel alternatives



VATTENFALL

Benchmarking

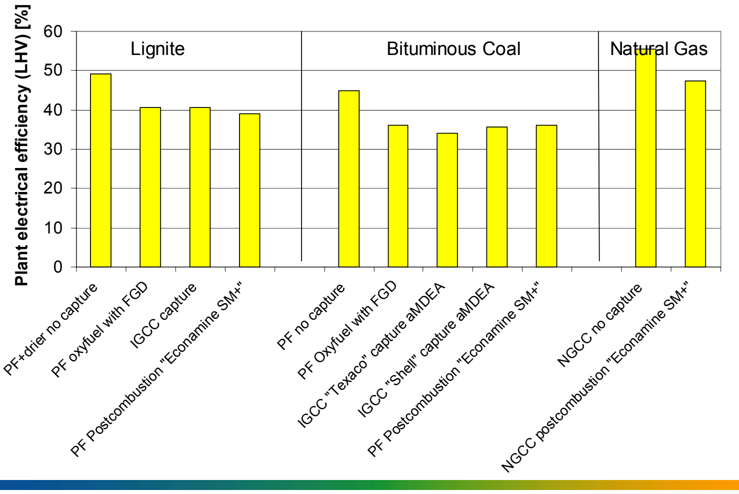
Oxyfuel PF alternative

vs.

Other generation technologies and fuels

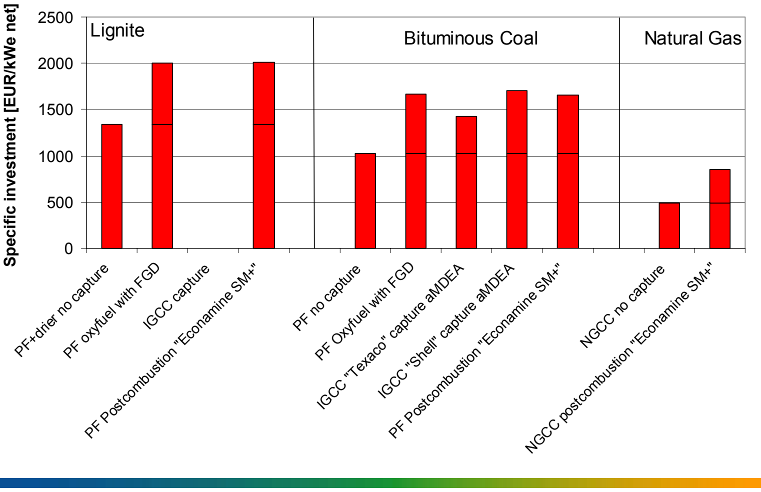
VATTENFALL

Net efficiencies (LHV) with and without CO2 capture



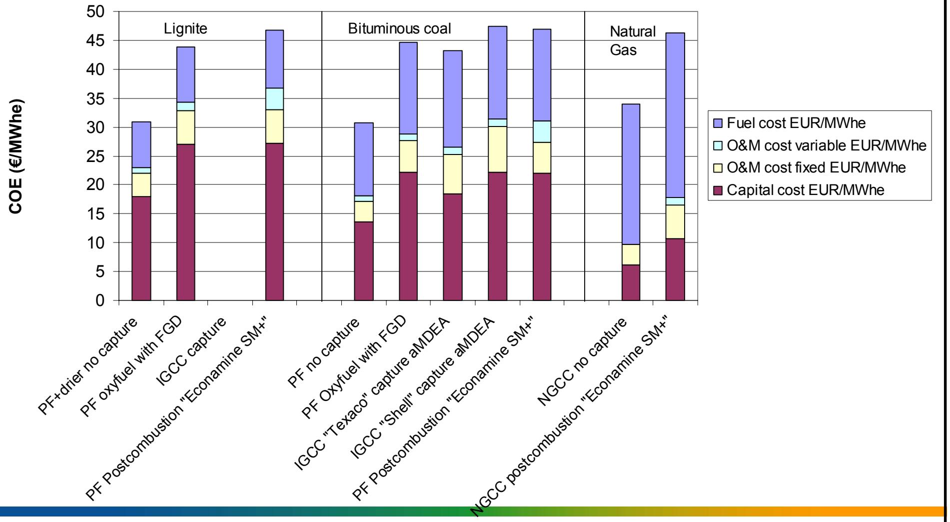
© Vattenfall AB 39 VATTENFALL

Specific investments with and without CO_2 capture



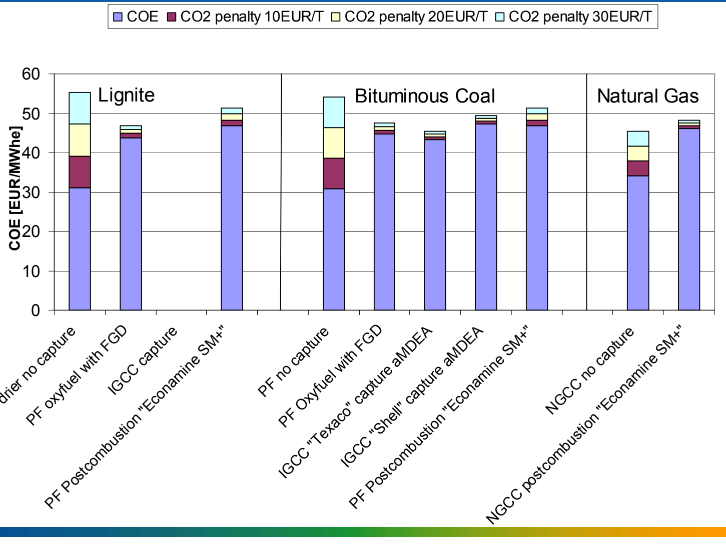
© Vattenfall AB 40 VATTENFALL

Cost of electricity for different options



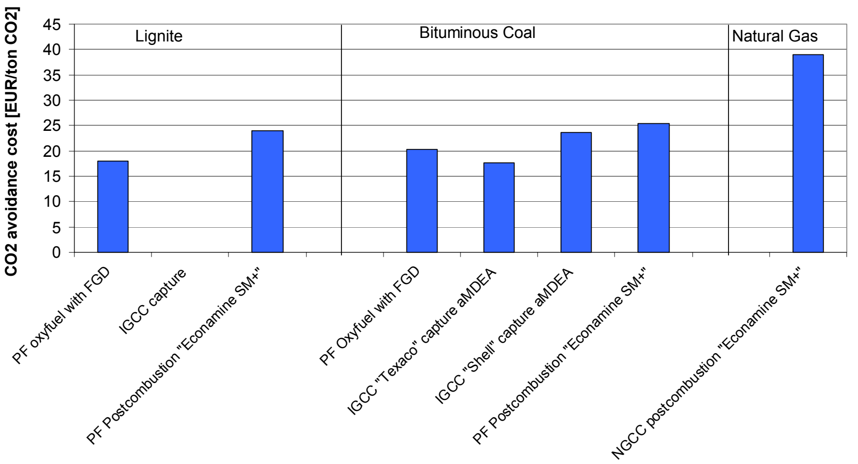
© Vattenfall AB 41 VATTENFALL

Total generation cost with CO_2 penalty



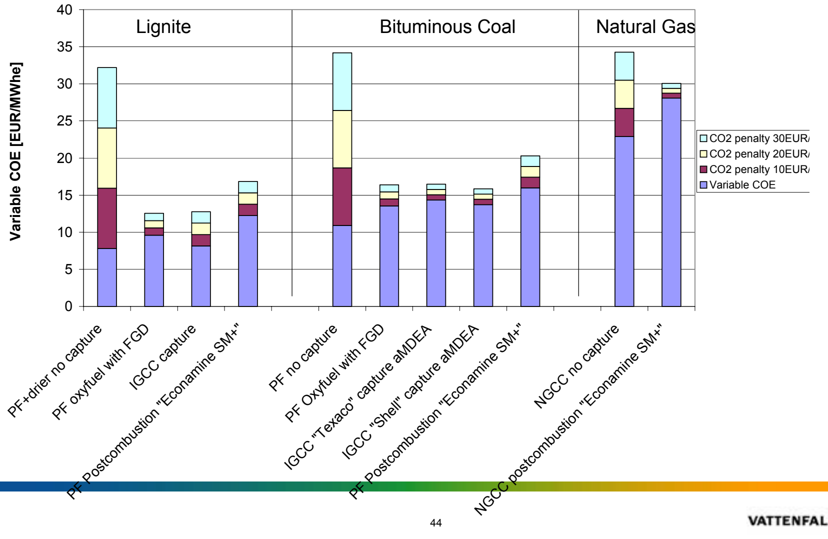
© Vattenfall AB 42 VATTENFALL

CO_2 Avoidance cost

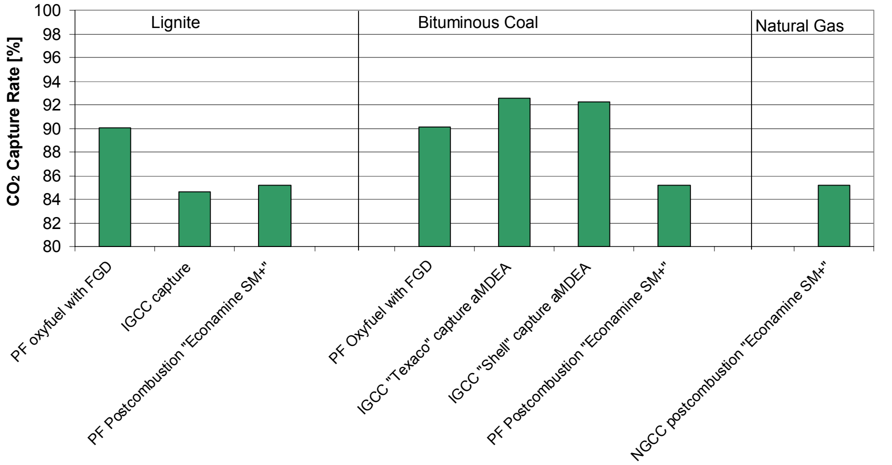


Variable cost of electricity

Figure 9: Variable COE including CO2 emission penalty



CO2 capture rate



VATTENFALL

Exchange of plants reduction of CO_2

Conclusions

VATTENFALL

Capture technologies

- All capture alternatives based on coal show COEs differing a little (43 - 47 €/MWhe)
  - Oxyfuel is a promising alternative – around 45 €/MWhe for both bituminous coal and lignite
- Cost of electricity for capture alternatives with natural gas are at similar level as the the ones for coal, considering the uncertainties in the estimates
- CO_2 avoidance cost around 20 €/ton CO_2 (16-24 €/ton) for coal
  - Note that the IGCC case uses IGCC as reference case, the CO_2 avoidance cost increases if PF is used as reference
- CO_2 avoidance cost around 40 €/ton for natural gas cases
- With a CO_2 emission penalty of 20 €/ton, the competition is between coal fired plants with capture and natural gas plants without capture.

VATTENFALL

Capture technologies year 2020 status

- All capture alternatives based on coal show similar COEs (34 - 38 €/MWhe)
  - For the oxyfuel case, only improvements in basic steam turbine technology has been accounted for, there is still a potential to improve process parts related to the oxyfuel conceptand air separation. Oxyfuel is still a promising alternative!
- Capture alternatives for natural gas are at similar level as the the ones for coal, considering the uncertainties in the estimates
- CO_2 avoidance cost around 17 -18 €/ton CO_2 for PF coal, IGCC 2020 about 7 €/ton
  - OBS that IGCC case uses IGCC as reference case, the CO_2 avoidance cost increases if PF is used as a reference
- CO_2 avoidance cost around 27 €/ton for natural gas cases

VATTENFALL

CO_2 free power plant - Why oxyfuel technology ?

1. Numerous different views on costs for technologies exist. Our internal studies point at oxyfuel as the least expensive.
2. We have investigated the IGCC technology thoroughly. We do not see it competitive unless very specific conditions. It is calculated slightly more expensive at present.
   - The availability and the reliability must be increased considerably and technical performance must be increased
3. Post combustion is commercially available at present up to the size 500 MW. It is calculated more expensive at present.
   - The energy consumption for regenerating the absorbent must come down considerably to make it competitive.
4. We have good experience from PC technology. We operate 7 large supercritical units with hard coal and lignite. We build 3 new at present. Our German competitors also build several new units at present.

VATTENFALL

Computer simulation of the new units in Hamburg (Moorburg) 2 x 750 MW hard coal

VATTENFALL

Computer simulation of the new Boxberg R unit 660 MW- lignite

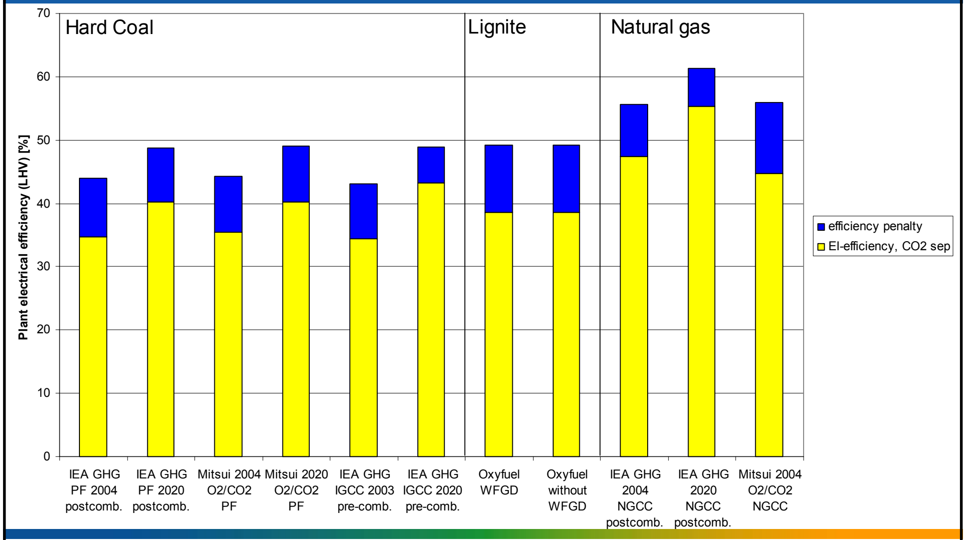
VATTENFALL

CO_2 free power plant

Back up

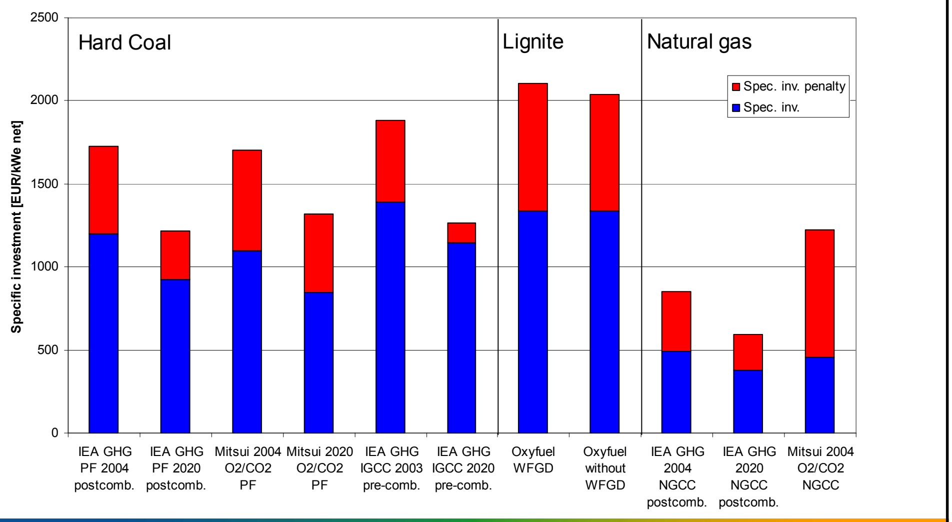
VATTENFALL

Electric efficiency with and without CO_2 capture



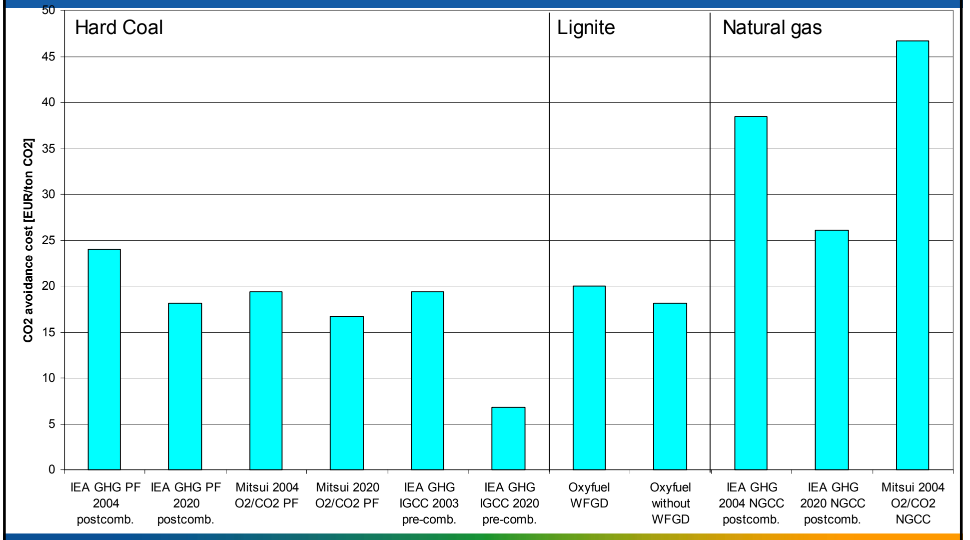
VATTENFALL

Specific investment cost with and without CO_2 capture



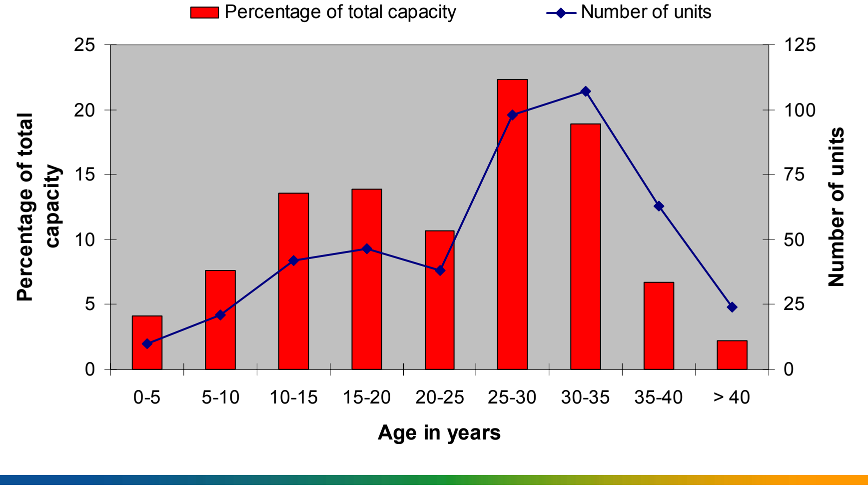
VATTENFALL

CO_2 avoidance cost



VATTENFALL

Age of coal fired plants



VATTENFALL

Work performance IGCC

- 6 cases studied
- 3 cases with and 3 cases without CO_2- capture

Data from
- IEA-reports as GHG PH4/19
- ENCAP SP2
- DOE - reports
- TU Dresden
- BASF
- GT World Handbook

Calculations with
- Ebsilon
- Gate for the gasturbine
- Shift med Excel and Aspen Plus (verification)

VATTENFALL

Choice of av Acid gas removal

aMDEA	Activivated Methyl-Di-Ethanol-Amine, technology offered by BASF.
DEA	di-ethanol-amine
NMP	n-methyl-2 pyrrolidon
DGA	di-glycol-amine
DMPEG	dimethyl-ether-polyethylene-glycol
Purisol	NMP (n-methyl-2 pyrrolidon) technology from Lurgi
Rectisol	Cold (-60ºC) Methanol as solvent
Selexol	Physical solvent with dimethyl ether of polyethylene glycol
Sulfinol	MDEA technology with license from Shell

VATTENFALL

Technical / economical evaluation

	VUAB IGCC Dry	VUAB IGCC Dry CO_2	VUAB IGCC Wet	VUAB IGCC Wet CO_2	VUAB Wet no quench	VUAB Wet no quench CO_2	IGCC Shell	IGCC Shell CO_2	IGCC Texaco	IGCC Texaco CO_2
Gasification press. [bar]	25	25	25	25	25	25	37	37	65	65
AGR	aMDEA	aMDEA	aMDEA	aMDEA	aMDEA	aMDEA	aMDEA	aMDEA	Selexol	Selexol
GT press. ratio	17	17	17	17	17	17	15,8	15,8	15,8	15,8
GT firing temp. [C]	1401,5	1401,5	1401,5	1401,5	1401,5	1401,5	1352	1352	1352	1352
Coal LHV [kJ/kg]	26016	26016	26016	26016	26016	26016	26016	26016	26016	26016
Coal [MW]	1821,6	1976,5	1891,7	2033,3	1929,1	1983,5	1800,8	1950,3	2177,3	2322,5
El. Gross [MW]	939,7	885,8	906,6	876,3	976,5	876,3	909,8	883,3	988,7	979,9
Aux. Cons. [MW]	110,1	182	117,5	187	122,4	184,1	132,9	199,2	160,2	237,1
El. Net [MW]	829,6	703,8	789,1	689,3	854,1	692,2	776,9	684,1	828,5	742,8
η_e [%]	45,5	35,6	41,7	33,9	44,3	34,9	43,1	35,1	38,0	32,0
Tot. invest. [MEUR]	935,4	1044,9	769,4	856,3	943,8	982,6	936,8	1038,6	865	925,4
Spec. inv. [EUR/kWe]	1297	1707	1121	1429	1271	1632	1387	1746	1200	1432,8

- In all cases sour shift is used
- In the total investment 5% addition for"owners cost" and 10% för "contingencies" are included

VATTENFALL

Inaugural Workshop

International Oxy-Combustion Research Network

Vattenfall Europe Mining and Generation AG Head Office
Cottbus, Germany

29th and 30th November 2005

PRESENTATION - 04

Vattenfall's Activities on Oxy-Fuel Combustion Studies

by:

Prof. Lars Stromberg
Vattenfall AB, Sweden

This page is intentionally left blank

IEA GHG Workshop on Oxyfuel
Vattenfall's activities

Cottbus 29-30th November 2005
Cottbus, Germany

Lars Strömberg
Vattenfall AB
Corporate Strategies
Berlin / Stockholm

VATTENFALL

The Vattenfall Group

- Vattenfall is one of the major Energy companies in Europe
- Vattenfall sells almost 200 TWh electricity
  - The main part is produced by hydropower, nuclear power, coal and natural gas.
  - A smaller part is produced by biofuels and wind power
  - About 20 TWh is produced in combined heat and power plants
- Vattenfall also sell about 40 TWh heat
  - The main part is produced by biofuels, coal and gas in cogeneration plants
- Vattenfall emits almost 90 million tons of CO_2 per annum

VATTENFALL

Power Plant Lippendorf

© Vattenfall AB 3 VATTENFALL

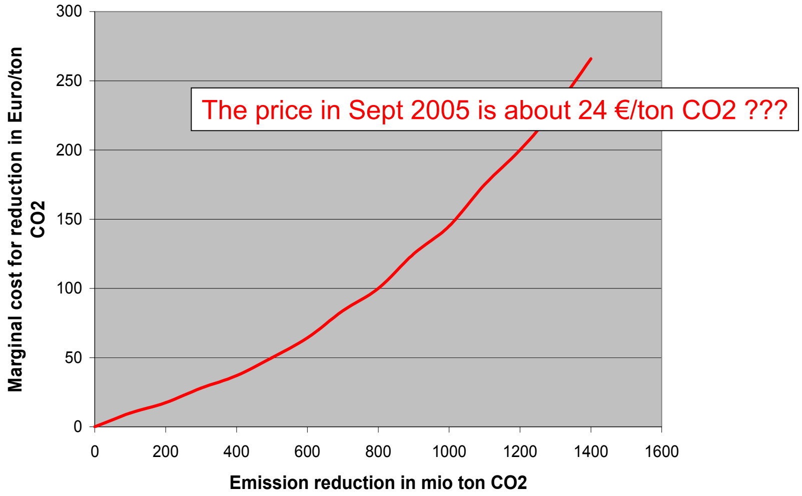
Emission Trading

Emission Trading sets the commercial framework for new technology in Europe

© Vattenfall AB 4 VATTENFALL

Marginal cost vs. Reduction of CO2 emissions in EUR/ton CO2

Source: ECOFYS Economic evaluation of sectorial reduction objectives for climate change

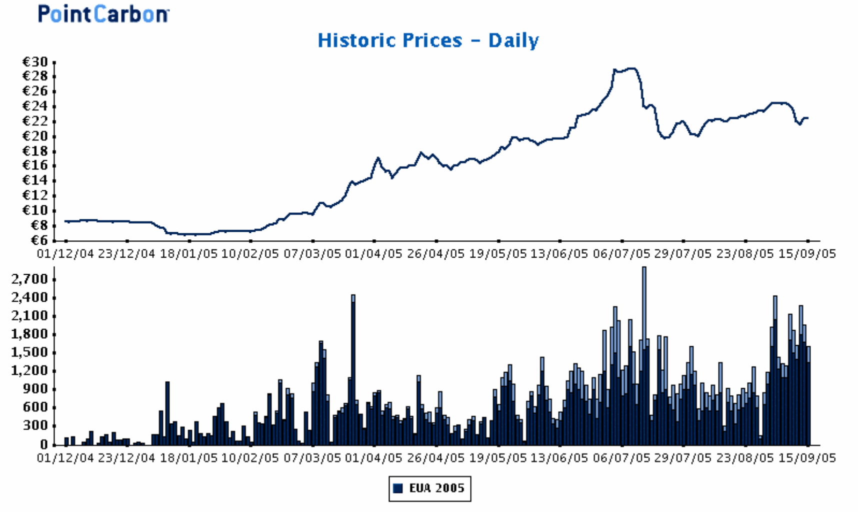


© Vattenfall AB

5

VATTENFALL

European CO_2 trading system Sept. 2005



© Vattenfall AB

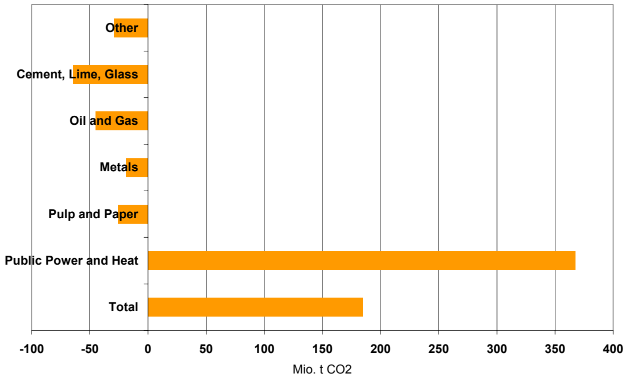
6

VATTENFALL

Allocations in the European trading system

In total 12 000 units is included in the trading system. In the National allocation plans 2 100 Mton/year or 6300 Mtons for three years have been distributed.

The deficit is calculated to 180 Mton for 3 years. The power industry has a deficit of 360 Mton. Other sectors have an overallocation.



VATTENFALL

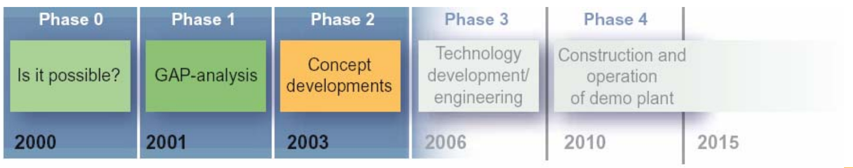
CO_2 free power plant

The CO2 free Power Plant project

VATTENFALL

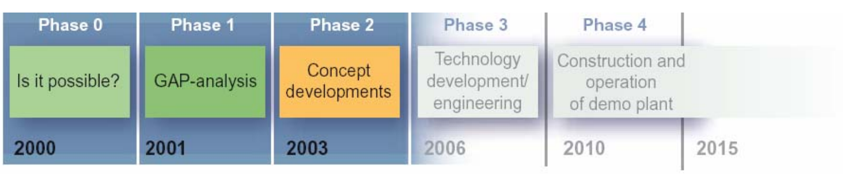
The CO_2 free power plant ; The Pilot

- The project "CO_2 free power plant" has been active since 2001. It will end with a proposal of how to build a full size demonstration plant. A pre-engineering phase for a demo is planned during 2008 - 2010
- As part of this process several pilot plants are needed
- Vattenfall has decided to build one of these pilot plants in Germany



  VATTENFALL

CO_2 free Power Plant
15 years of research and development



- The technical target is expressed as:
  - Total cost below 20 €/ton stored CO_2
  - Capture efficiency above 95 %
- The project contains 5 stages
  - We are in the end of the Concept development phase, which contains pilot plant(s)
  - In 2008 we shall have enough knowledge to propose a feasible demoplant location, structure, technology and budget
  - Construction of a full scale demo plant is scheduled to start 2010

  VATTENFALL

Focus of the work to reduce CO_2

Focus is different for each part of the chain

Capture
- Develop and evaluate the concepts
- Cost reduction
- Validation and verification

Transport
- Apply known concepts to scale
- How to develop an infrastructure

Storage
- Verification of technology
- Potential, actual availability
- Risk, Security and Environmental consequences
- Building confidence and acceptance

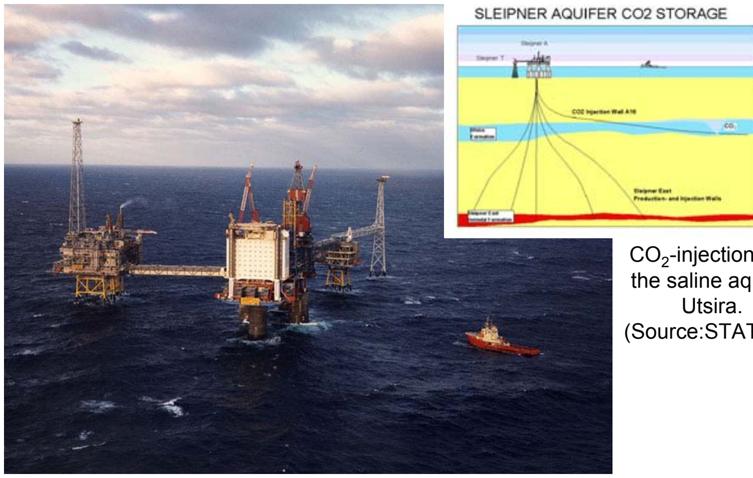
VATTENFALL

CO_2 free power plant

Storage and transport

VATTENFALL

Storage of CO_2 in a Saline Aquifer under the North Sea

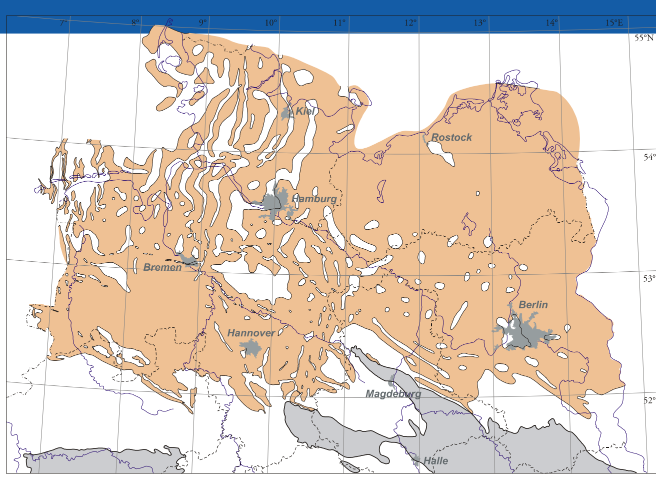


CO_2-injection into the saline aquifer Utsira. (Source:STATOIL)

The Sleipner field. Oil and gas production facilities. (Source: STATOIL)

VATTENFALL

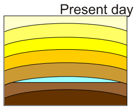
Storage Capacity, saline aquifers



Present day distribution of the Rhetian - aquifers (a. DIENER et al. 1984, FRISCH & KOCKEL 1998)

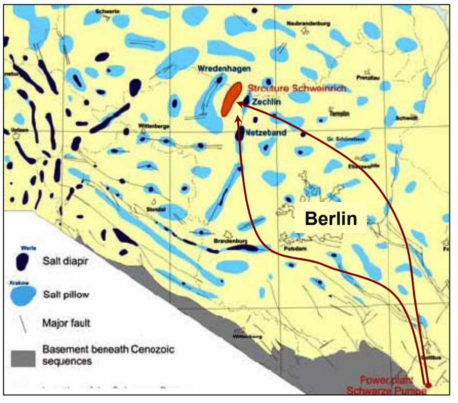
There exists more storage capacity within Europe (and in the world) than the remaining fossil fuels

Source:
Franz May,
Peter Gerling,
Paul Krull
Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover



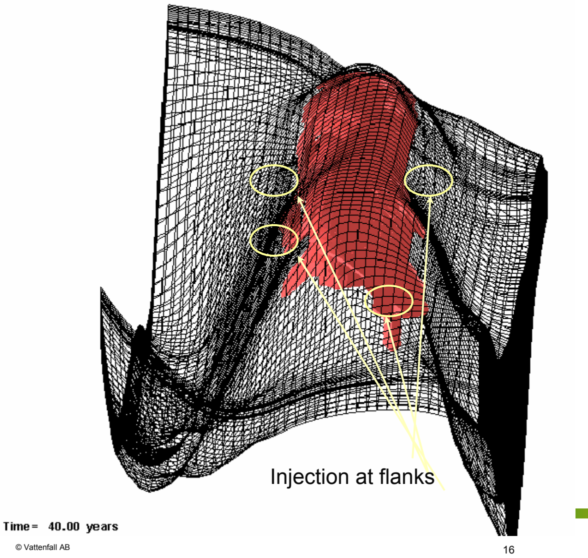
VATTENFALL

CO_2 Transport and storage Schweinrich structure



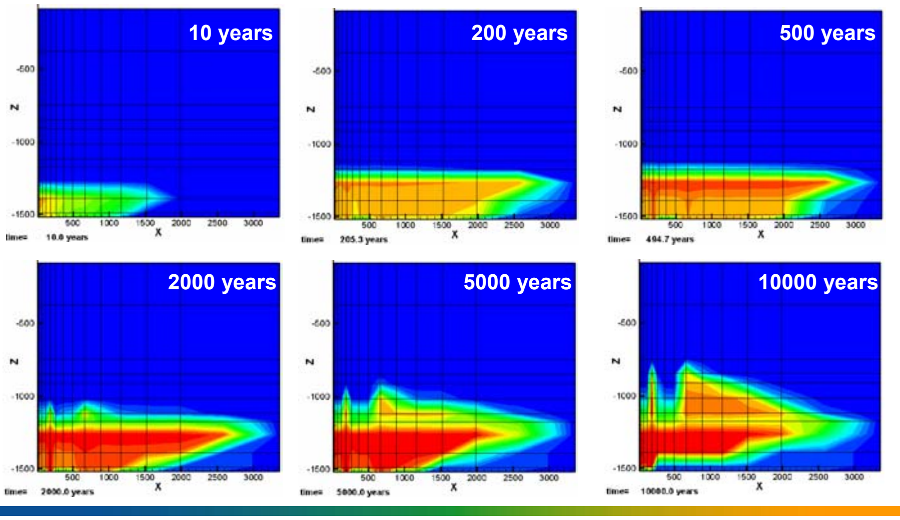
- Two pipeline transport routes are possible
- Both routes can be designed to follow existing pipeline corridors >90%
- Structure can contain 1,4 billion ton of CO2, equivalent to about emissions from 6000 MW their whole lifetime

Reservoir simulation – 40 year model



- Due to buoyancy, the CO_2 strive against the top of the formation
- The CO_2 spreads in the whole reservoir
- Conclusion: It is possible to inject 400 Mt CO_2

Geological structure modelling. Schweinrich



CO_2 storage cost

Storage at Schweinrich of 10 Mton CO_2 per year over 40 years:

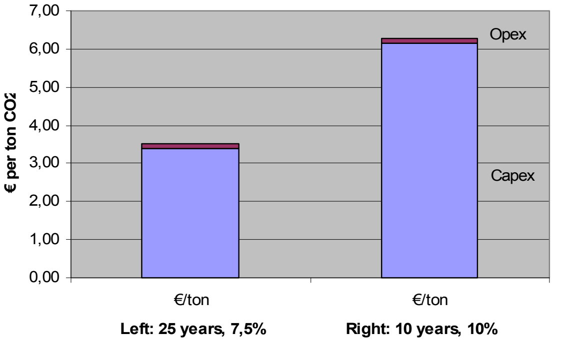
Parameter	Units	Base case	High cost case
Discount rate	%	12	18
Number of wells	-	6	12
Drilling cost	€/m	1000	2000
Platform cost	M€	20	50
- Feasibility phase		0.3	1
- Investigation phase		5.7	9
- Injection equipment		14	40
O&M	M€	3	10
Post operational cost	M€	0.3	1
Resulting cost	€/ton CO_2	0.7	3

Fictive cost calculations using tool developed in EU-funded GESTCO project:

CO_2 transport cost:

Transport to Schweinrich from Schwarze Pumpe power plant:

- Distance 320 km
- 10 Mton CO_2 per year over 40 years:



VATTENFALL

CO_2 free power plant

Pilot Plant

VATTENFALL

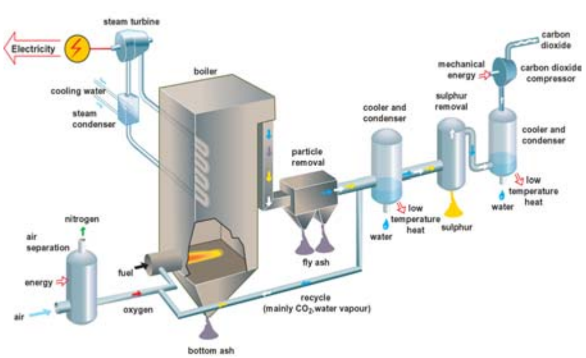
The forecast - upscaling

2004	2008	2015	2020
Test plant **0,1-0,5 MW_{th}** **< 3 Mio. €**	**Pilot plant** **30 MW_{th}** **< 40 Mio. €**	**Demonstration plant** **300-600 MW_{th}** **~ 400 Mio. €**	**Commercial plant** **~ 1,000 MW_{th}**
• Research • Basic principles • Combustion characteristics	• Demonstration of the process chain • Interaction of components • Validation of basic principles and scale-up criteria • Long term characteristics • Non-commercial	• Verification and optimization of the component choice, the process and reduction of risks • Must be commercially viable incl. subsidies	• Competitive in the market at that time • No subsidies

© Vattenfall AB 21 VATTENFALL

Technology

- The size of the plant will be about 30 MWth and the energy will be utilized



- The technology used is the “Oxyfuel technology” also characterized as CO_2/O_2 combustion
- The plant will be built adjacent to the Schwarze Pumpe Power plant and will utilize all necessary infrastructure there.
- Fuel will be lignite, and hard coal

© Vattenfall AB 22 VATTENFALL

Plant Content

- The pilot plant will comprise a full chain including boiler, gas cleaning, CO_2 processing and cleaning and an air separation unit:
  - It will produce liquid CO_2 to an intermediate tank storage, useful for truck transport.
  - It is prepared for later connection to a geological storage project, maybe including pipeline transport.
  - Capture rate of CO_2 exceeds 90 % (Target is higher in a full size plant)
- The contaminants from the combustion will be almost completely captured and separated. It will be close to a "zero emission plant" if CO_2 is stored
  - There will be almost no emissions to the atmosphere
  - Sulfur will be handled in form of gypsum as in the large SP plant.
  - Ash will be handled and reused as in the large plant
  - If necessary the nitrogen oxides will be treated in a small bleed-off gas stream
- The CO_2 will not be permanently stored initially. It will be released into the atmosphere.

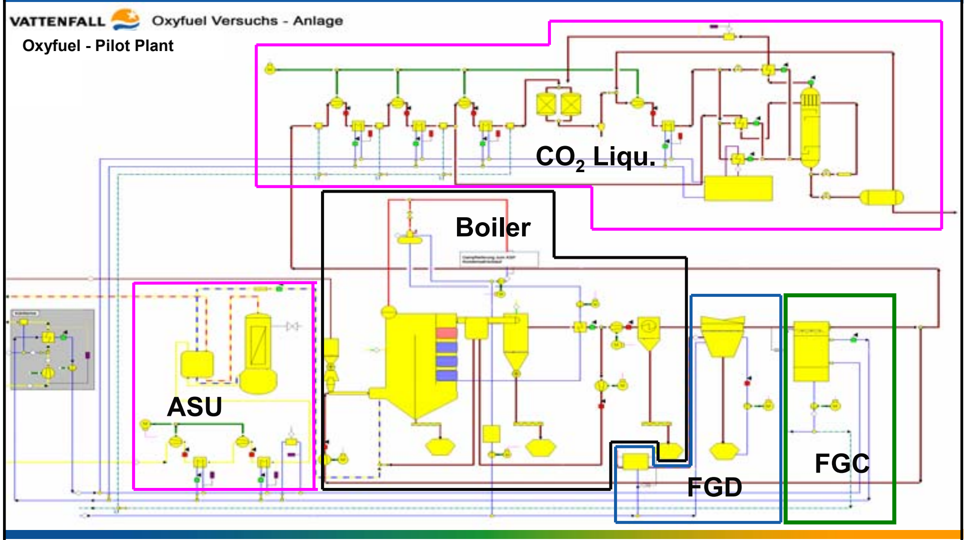
VATTENFALL

Time schedule, budget

- Time schedule for the project is still depending on negotiations with the vendors and the permission process. The permission process is still uncertain.
- Present estimation gives that the plant can produce CO_2 in mid 2008. The ambition is, if circumstances permit, to shorten the timescale. Physical construction starts in 2006
- The budget for the plant includes a three year test program
- The estimated cost of the plant itself is 37 mio € and the test program will cost about 20 mio €
- Industrial and institutional partners are invited to participate, reduce cost, contribute with experience and share knowledge

VATTENFALL

Identification of the different packages



VATTENFALL

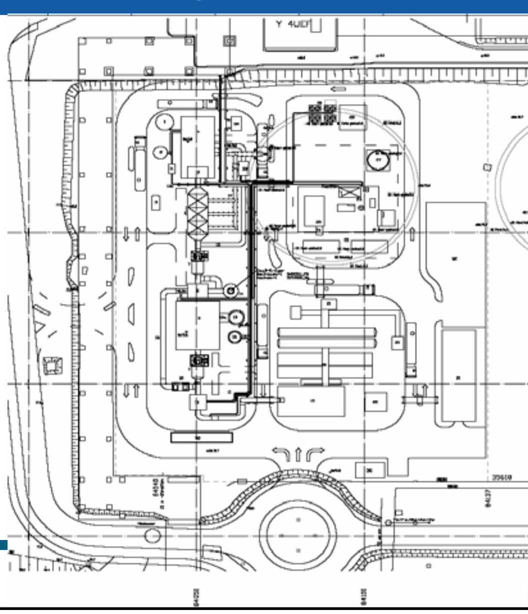
Schwarze Pumpe power plant

VATTENFALL

Construction area

VATTENFALL

Working status of Lay out



Required Area:

14.500 m³

VATTENFALL

Reduction of CO_2

Why oxyfuel technology ????

VATTENFALL

CO_2 free power plant - Why oxyfuel technology ?

1. Numerous different views on costs for technologies exist. Our internal studies point at oxyfuel as the least expensive.
2. We have investigated the IGCC technology thoroughly. We do not see it competitive unless very specific conditions. It is calculated slightly more expensive at present.
   - The availability and the reliability must be increased considerably and technical performance must be increased
3. Post combustion is commercially available at present up to the size 500 MW. It is calculated more expensive at present.
   - The energy consumption for regenerating the absorbent must be reduced considerably to make it competitive.
4. We have good experience from PC technology. We operate 5 large supercritical plants with hard coal and lignite. We build 3 new at present. Our German competitors also build several new units at present.

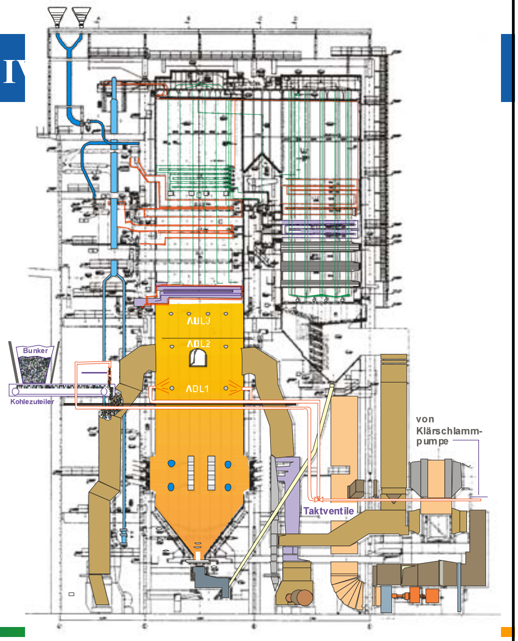
VATTENFALL

Boxberg I

Why Oxy-fuel technology ?

We work with all three (four) technologies, but:

- Oxyfuel technology is the technology giving lowest costs at present
- It is suitable for coal and have relatively little development work left
- We can build on our good experience with present PF technology



VATTENFALL

Exchange of plants reduction of CO_2

Conclusions

VATTENFALL

Conclusions from analysis - Reduction of CO_2

- Carbon capture and storage from Coal fired Power plants can be done at a cost close to 20 €/ton CO2
  - Capture at about 15 €/ton of CO2
  - Storage at lower than 2 €/ton CO2
  - Transport depending on distance and volume, but 5 €/ton of CO2 for large plants on shore
- More than enough storage capacity on shore and off shore is at hand in saline aquifers
- Technology choice is not yet made. Oxyfuel is preferred technology in Vattenfall at present
- The commercial choice stands between Gasfired CC without CCS, taking the penalty of CO2 emission, and Coal fired plants with CCS

Taking responsibilty

- Lord Oxburgh, former chairman of Shell Transport and Trading:

  "CCS is absolutely essential if the world is serious about limiting greenhouse gas emissions“

- The new report from the Intergovernmental Panel on Climate Change (IPCC) concludes:

  “CCS could achieve more than half of the emissions reductions necessary to mitigate climate change up to 2100”

Vattenfall agrees with this. We also believe CCS is needed to fulfill our climate goals

Computer simulation of the new units in Hamburg (Moorburg) 2 x 750 MW hard coal

© Vattenfall AB 35 VATTENFALL

Computer simulation of the new Boxberg R unit 660 MW- lignite

© Vattenfall AB 36 VATTENFALL

Inaugural Workshop

International Oxy-Combustion Research Network

Vattenfall Europe Mining and Generation AG Head Office
Cottbus, Germany

29th and 30th November 2005

PRESENTATION - 05

An Overview of Oxy-Fuel Combustion R&D Programme in CANMET

by:

Kourosh Zanganeh
CANMET, Canada

IEA GREENHOUSE GAS R&D PROGRAMME

This page is intentionally left blank

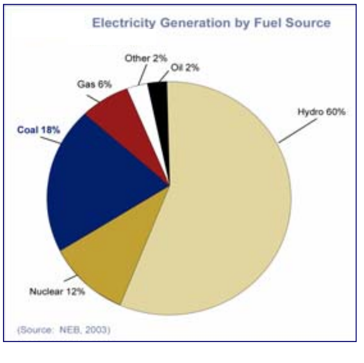
Oxy-Fuel Combustion & CO_2 Capture Research Program at CANMET

Dr. Kourosh E. Zanganeh
Clean Electric Power Generation
CANMET Energy Technology Centre (CETC) – Ottawa
Natural Resources Canada

www.nrcan.gc.ca

IEA Oxy-Fuel Combustion Workshop
November 29-30, 2005, Cottbus, Germany

Canada's Energy Sources & Future Outlook



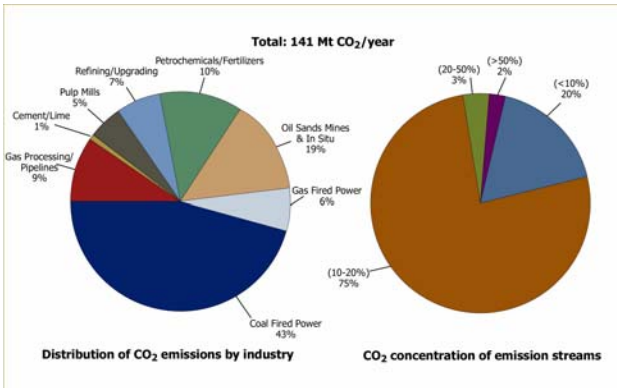
NRCan's "Business as Usual" Scenario
In 2000 electricity generated from fossil fuels: 26%
In 2020 electricity generation from fossil fuels: 35%

- Canada has a diversified portfolio of energy sources
- Based on the future projections, Canada will becoming more depending on fossil fuels for electricity generation
- With sharp increases in oil and gas prices, coal may becoming the fuel of choice
- Fortunately, Canada has a large deposit of coal
- *Clean coal technology (CCT)* can help to secure the position of coal among other energy sources

C E T C CANMET ENERGY TECHNOLOGY CENTRE

GHG Emissions

- Canada has ratified the Kyoto Protocol and agreed to lower its GHG emissions to 6% below 1990 levels during 2008 – 2012 (an estimated gap of 240 to 280 Mt for all sources).



Natural Resources Canada Ressources naturelles Canada 3 Canada

C E T C CANMET ENERGY TECHNOLOGY CENTRE

Canada's Climate Change Plan 2005

"*It is estimated that the approaches outlined in the Plan, with an associated federal investment in the range of $10 billion through 2012, could reduce GHG emissions by about 270 Mt annually in the 2008–2012 period*."

www.climatechange.gc.ca

Funding provided in 2005 budget

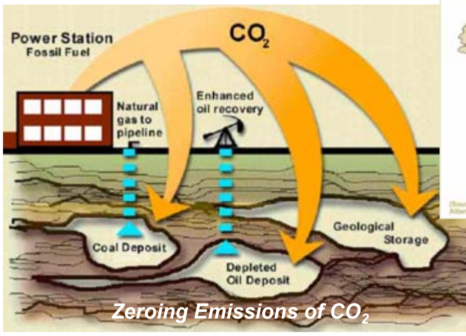
- **Climate Fund**: $1 billion (purchase GHG reduction & removal credits in Canada and abroad)
- **Partnership Fund**: $250 million (could grow to $2-$3 billion over the next decade)
- **Renewable**: total of $600 million ($200M for Wind PPI, $100M Renewable PPI, and $300M tax incentives)
- **Programs**: $2 billion (for existing climate change programs)

Natural Resources Canada Ressources naturelles Canada 4 Canada

C E T C CANMET ENERGY TECHNOLOGY CENTRE

CO_2 Capture & Storage (CCS)

- CCS could provide a bridge to our energy future in a carbon-constrained energy economy
- The *Western Canada Sedimentary Basin* provides a unique opportunity for storage of CO_2



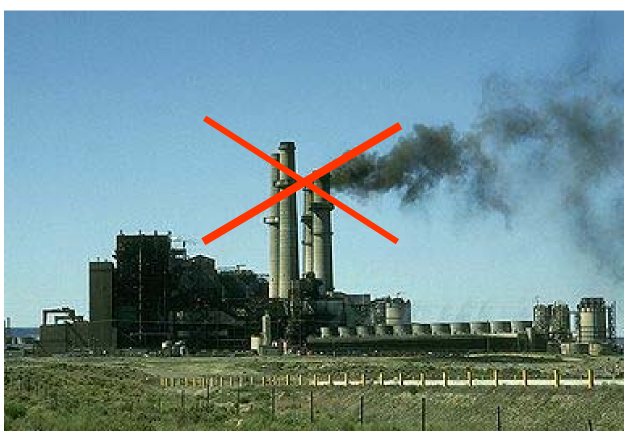
IEA Weyburn CO_2 Monitoring and Storage Project (1 Mt/yr of CO_2)

Natural Resources Canada Ressources naturelles Canada 5 Canada

C E T C CANMET ENERGY TECHNOLOGY CENTRE

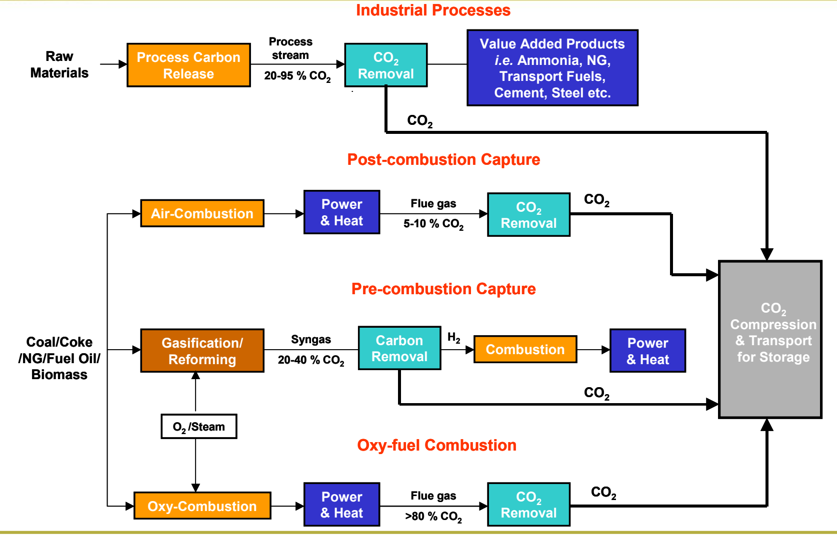
Zero-Emission Technologies (ZETs)

- ZETs - a priority within Canada's climate change response options and a part of a sustainable development strategy



Natural Resources Canada Ressources naturelles Canada 6 Canada

Zero-Emission Technology Pathways

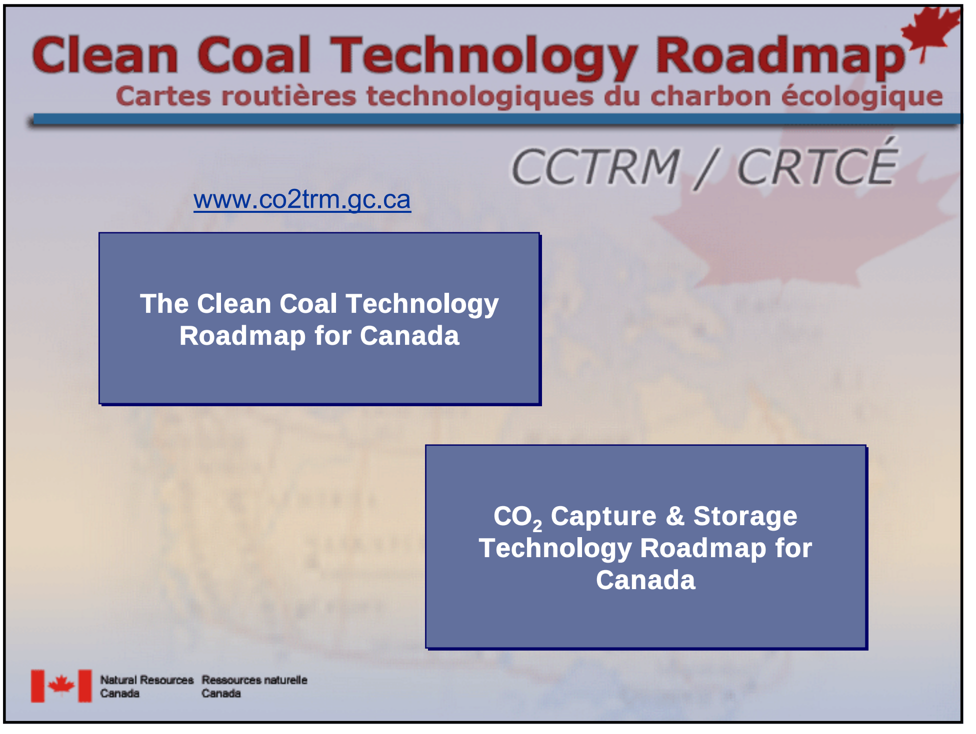


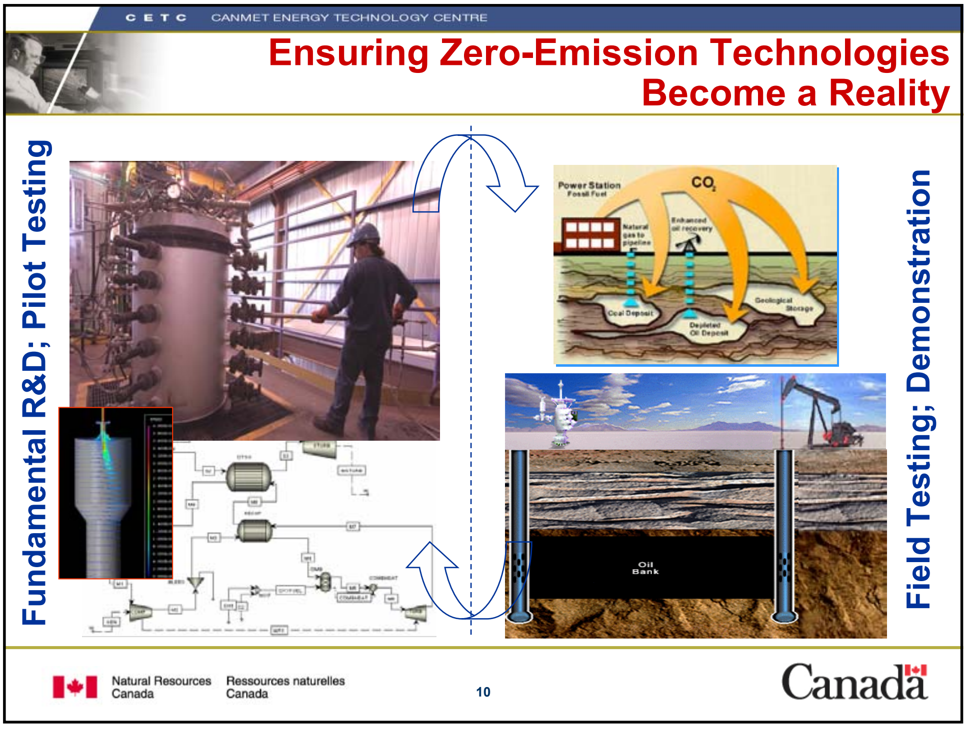
Program Components and Major Activities

Zero-Emission Technologies & CO_2 Capture
- CETC Oxy-Fuel/CO_2 Research Consortium
- T&I Zero-Emission Oxy-Fuel Combustion
- CO_2 Compression Unit
- Multi-Pollutant and Hg Control for Oxy-Coal Combustion
- Oxy-Fuel FBC Technology (with FBC&G Group)

University Projects
- Raven Zero-Emission Gas Turbine (Carleton Univ.)
- CO_2 Capture using Amine Scrubbing (Univ. of Regina)
- CO_2 Capture in WCSB Hydrogen Plants (Univ. of Waterloo)
- Electricity Production with Coal, NG and SOFC (Univ. of Waterloo)

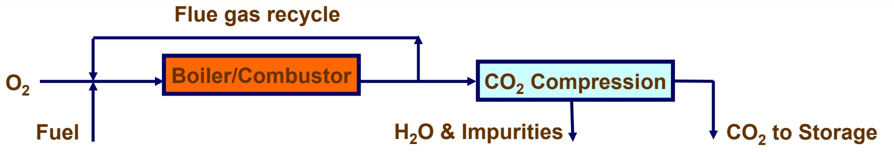
Technology Road-mapping for Canada
- Clean Coal Technology Roadmap
- CO_2 Capture and Storage Technology Roadmap


Clean Coal Technology Roadmap
Cartes routières technologiques du charbon écologique
CCTRM / CRTCÉ
www.co2trm.gc.ca
The Clean Coal Technology Roadmap for Canada
CO_2 Capture & Storage Technology Roadmap for Canada
Natural Resources Canada
Ressources naturelle Canada


C E T C
CANMET ENERGY TECHNOLOGY CENTRE
Ensuring Zero-Emission Technologies Become a Reality
Fundamental R&D; Pilot Testing
Field Testing; Demonstration
Power Station
CO_2
Oil Bank
Natural Resources Canada
Ressources naturelles Canada
10
Canada

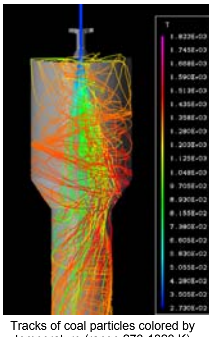
CETC CANMET ENERGY TECHNOLOGY CENTRE

CETC Oxy-Fuel/CO_2 Research Consortium



Goal: To develop oxy-fuel combustion technologies for improved efficiency and capture of CO_2 from flue gas streams

- **Burner development**
- **Boiler performance simulation**
- **Multi-pollutant capture integration**
- **Advanced process and cycle development**
- **Field demonstration of oxy-fuel combustion**
- **CO_2 capture and compression unit development**



Tracks of coal particles colored by temperature (range 273-1823 K)

Natural Resources Canada Ressources naturelles Canada 11 Canada

CETC CANMET ENERGY TECHNOLOGY CENTRE

Status: Program started in 1994 and is currently in Phase 8; the project has been endorsed by CSLF

Funding: About \$1M (Cnd.) per year

Partners:

- **Canadian Electric Utilities**
- **Governments of Canada**
- **Government of Alberta**
- **Babcock and Wilcox**
- **US Dept. of Energy**

Participation: Other organizations can apply to become a member

Natural Resources Canada Ressources naturelles Canada 12 Canada

Acticities: focused on 1st generation oxy-fuel combustion systems and other enabling technologies

- Performed extensive experimental investigations using coal, coal slurry, bitumen and natural gas
- Studied the characteristics of oxy-fuel combustion with flue gas recirculation (FGR)
- Investigated oxy-fuel Brayton/Rankine cycles
- Performed solid oxide fuel cell (SOFC) modeling to explore potential for integration of fuel cell operating on syngas (H_2 & CO)
- Conducted multi-pollutant capture research in the condensing environment for integrated removal of fine particulates, SO_x and Hg

Outcomes: A unique knowledge database and a set of tools to facilitate the implementation of oxy-fuel technology with CO_2 capture

- Simulation and test results show that 1st generation oxy-fuel technology can be retrofitted to the existing coal-fired power plants
- Retrofit requires some modifications to the boiler system, but this leads to improved performance and lower NO_x emissions

New Directions: Activities now target advanced (2nd generation) oxy-fuel combustion units for

Minimizing recycle flow

Better integrated emission control technology

Zero emission gas turbine technology

Application of oxy-fuel combustion to CFB

CETC CANMET ENERGY TECHNOLOGY CENTRE

T&I Zero-Emission Fossil Fuel Combustion

Status: Project started in 2003 and currently in the 3rd year

Funding: Secured government funding of $2.3M (Cnd) for 5 years (2003 to 2008), with additional industry leverage

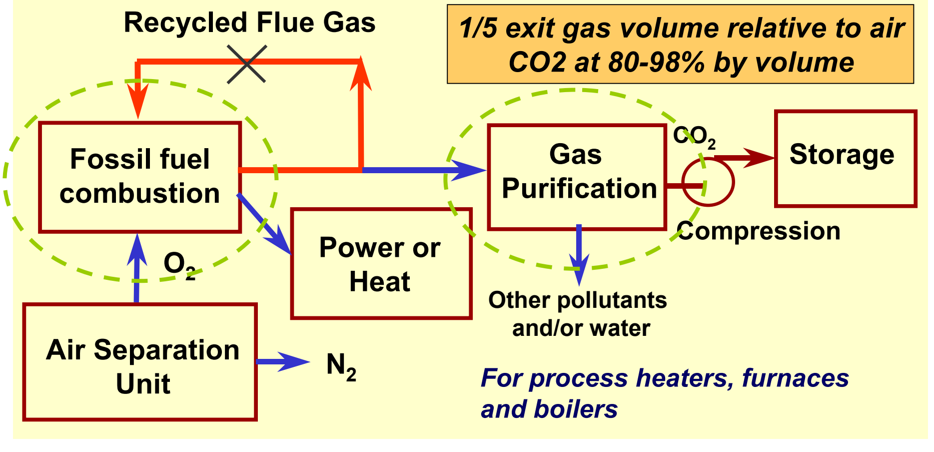
Technology areas: Focused on zero-emission combustion technologies

- Moving towards the 2nd generation of oxy-fuel combustion systems for power generation with CO_2 capture
- Developing new and integrated oxy-fuel combustion processes for advanced power/heat generation cycles
- CO_2 capture and compression performance testing & optimization

Natural Resources Canada Ressources naturelles Canada 15 Canada

CETC CANMET ENERGY TECHNOLOGY CENTRE

2nd Generation Oxy-Fuel Combustion Systems

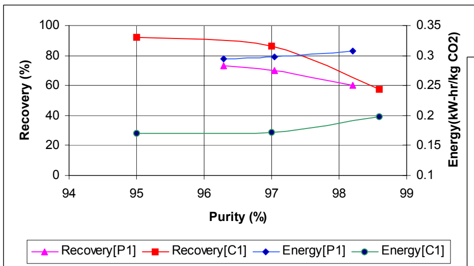


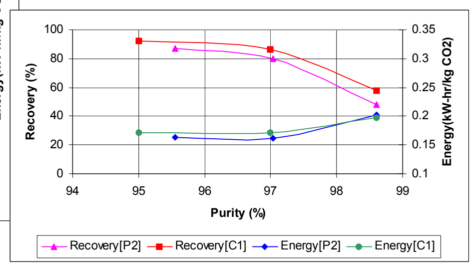
Natural Resources Canada Ressources naturelles Canada 16 Canada

C E T C CANMET ENERGY TECHNOLOGY CENTRE

Multi-Stage CO_2 Compression Processes

- Direct CO_2 compression and cooling
- CO_2 auto-refrigeration process (CO_2LDSEP™ - P1)
- CO2 compression/expansion process (CO_2LDSEP™ – P2)
- CETC's proprietary CO_2 compression process – C1

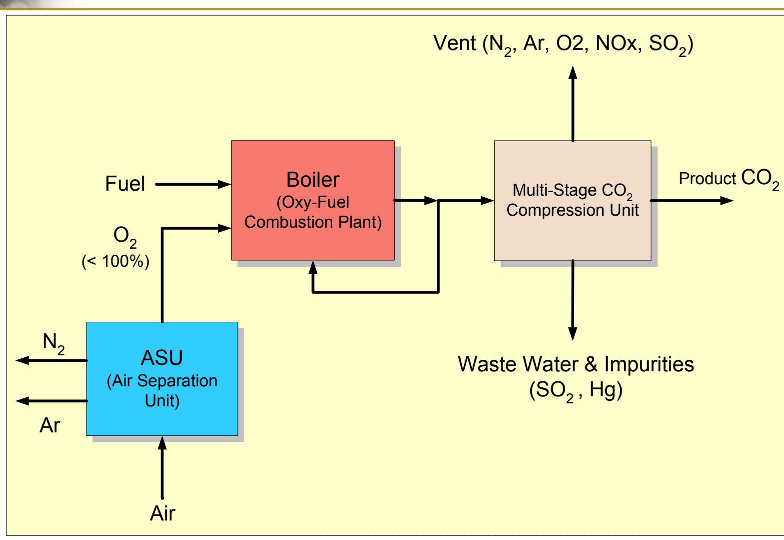




Natural Resources Canada Ressources naturelles Canada 17 Canada

C E T C CANMET ENERGY TECHNOLOGY CENTRE

Optimization of Integrated Oxy-Fuel Processes



Natural Resources Canada Ressources naturelles Canada 18 Canada

Oxy-Fuel Technologies under Development

R&D work at CETC is progressing towards 2nd generation oxy-fuel systems and relevant technologies

1. The 2nd generation oxy-fuel combustor design and process optimization
2. Oxy-steam combustion process development
3. Advanced oxy-fuel and oxy-steam burner design and development
4. Novel and efficient CO_2 capture and compression process development, pilot-scale unit design and implementation
5. Multi-pollutant sorbents for oxy-coal combustion
6. Zero emission gas turbine combined cycle
7. Other enabling technologies

Oxy-Fuel Opportunities and Challenges

Opportunities

- Produces a highly concentrated stream of CO2, ready for capture and storage
- With pure O2 combustion, the exit flue gas volume may be reduced to 1/5th of air-fired combustion
- Offers excellent opportunities for integrated emissions control through reduced flue gas flow
- Eliminates the need for downstream NO_x Control

Challenges

- Cost of oxygen production
- Lack of commercial demonstration
- Need for advanced materials for pure oxygen-fired combustion

CETC CANMET ENERGY TECHNOLOGY CENTRE

Canada & Saskatchewan MOU (Nov 24, 2005)

$40 million for initial feasibility work on two projects

- Funding is supported through the Partnership Fund
- $10+$10 million: initial work on a near zero-emission clean coal plant (~300 MW) by Saskpower to be built in southern Saskatchewan
- $10+$10 million: technical and economic studies for an industrial gasification and poly-generation facility near Belle Plain
- The funding supports design work needed to use the captured CO_2 in EOR operations, including CO_2 pipelines
- $4.5 billion: total estimated cost of the projects to be operational around 2011

Natural Resources Canada Ressources naturelles Canada 21 Canada

CETC CANMET ENERGY TECHNOLOGY CENTRE

Pilot-Scale Testing at CETC

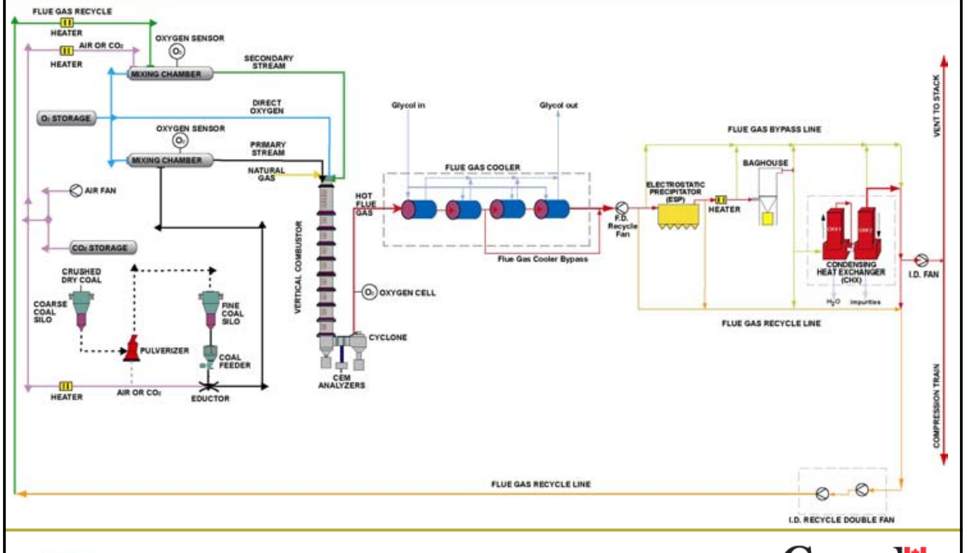
Vertical Combustor Research Facility (VCRF)

Natural Resources Canada Ressources naturelles Canada 22 Canada

Features & Capabilities (VCRF)

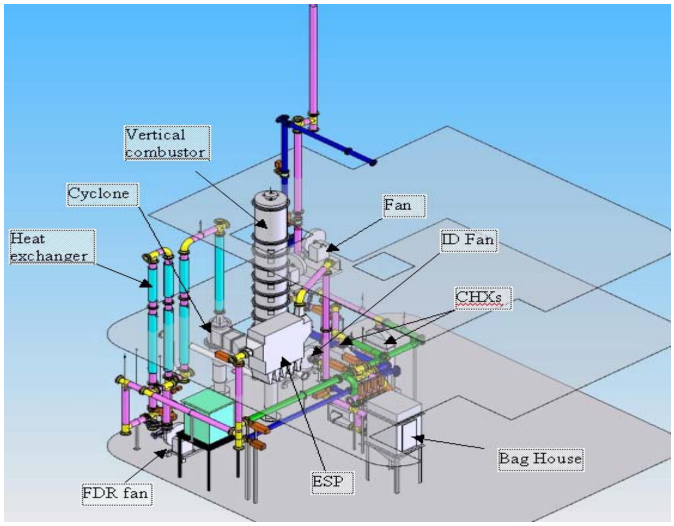
- Highly modular and flexible state-of-the-art air- and oxy-fired facility
- Has a nominal thermal output of about 0.3 MW
- NG, coal, coal slurry, oil and bitumen can be burned in a controlled environment
- Can be used to develop novel integrated multi-pollutant control technologies, including NO_x, SO_x, Hg and CO_2 capture
- Equipped with advanced process monitoring and control systems

Process Flow Diagram



C E T C CANMET ENERGY TECHNOLOGY CENTRE

Overview (VCRF)



Natural Resources Canada | Ressources naturelles Canada

25

Canada

C E T C CANMET ENERGY TECHNOLOGY CENTRE

Visit our Web Sites

www.cleanenergy.gc.ca

www.cetc.nrcan.gc.ca

Natural Resources Canada | Ressources naturelles Canada

26

Canada

C E T C CANMET ENERGY TECHNOLOGY CENTRE

Additional Web Sites

Corporate
http://www.cetc.nrcan.gc.ca/
http://www.cleanenergy.gc.ca/
www2.nrcan.gc.ca/es/es
exporttech.gc.ca

Industrial Innovation Group
www.cga.ca/
www.capp.ca/default.asp
www.caddet-ee.org
www.iea-coal.org.uk

www.climatechange.gc.ca/english/CCAF
www.worldbank.org/

Sustainable Built Environment
www.canren.gc.ca/
www.canwea.ca/
www.cansia.ca/
www.ekocomfort.com/
www.super-e.com
www.cdea.ca
www.sci.gc.ca/
www.ecbcs.org/

Hydrogen, Fuel Cells & Transportation
www.h2.ca/
www.nrcan.gc.ca/es/etb/ctfca/
www.greenfuels.org/assn.html
www.evac.ca/

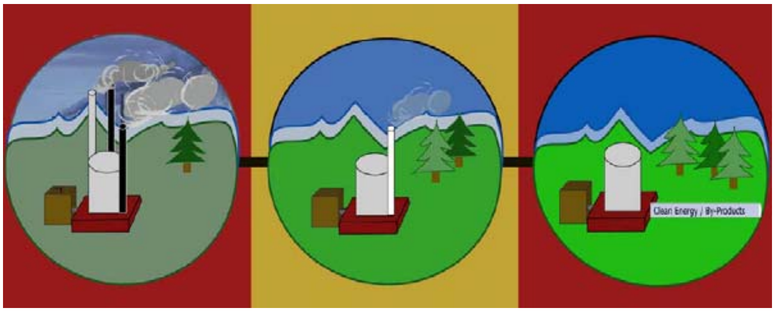
Clean Electric Power Generation
http://www.cleancoaltrm.gc.ca
http://www.co2trm.gc.ca
www.ieagreen.org.uk

Natural Resources Canada Ressources naturelles Canada

27

Canada

C E T C CANMET ENERGY TECHNOLOGY CENTRE



Thank You

Natural Resources Canada Ressources naturelles Canada

28

Canada

Inaugural Workshop

International Oxy-Combustion Research Network

Vattenfall Europe Mining and Generation AG Head Office
Cottbus, Germany

29th and 30th November 2005

PRESENTATION - 06

Fundamental Oxy-Fuel Combustion Research Carried Out within the ENCAP Project

by:

Klas Anderson
Chalmers University, Sweden

IEA GREENHOUSE GAS R&D PROGRAMME

This page is intentionally left blank

CHALMERS

University Stuttgart

Oxy-fuel workshop, Cottbus, 29-30th November 2005

Fundamental oxy-fuel combustion research carried out within the ENCAP project

KLAS ANDERSSON
Department of Energy and Environment, Chalmers University of Technology

CHALMERS

University Stuttgart

ENCAP Oxyfuel Boiler technologies - Participating Organizations

- Vattenfall AB, Sweden
- Energi E2 AS, Denmark
- Mitsui Babcock Energy Limited, UK
- L'Air Liquide, France
- Public Power Corporation S.A., Greece
- University of Stuttgart, Germany
- Chalmers University of Technology, Sweden
- Siemens Aktiengesellschaft, Germany
- ALSTOM Power Centrales Steam Power Plant, France
  ALSTOM Power Boilers SA, France
  ALSTOM Power Boiler GmbH, Germany
- RWE Power AG, Germany
- University of Ulster, United Kingdom

CHALMERS

University Stuttgart

Research on combustion fundamentals in Encap

- Increased knowledge on fundamentals of combustion behaviour and emission formation/reduction
- Basic combustion characteristics, data for validation of CFD modeling and to support selection of flue gas treatment technology.

  → coal combustion tests to characterize emission behavior, ash quality, particle temperatures etc under oxyfuel combustion conditions compared to air combustion

  → gas fired tests to identify and characterize differences in flame properties; gas concentrations, temperatures and radiation characteristics, between oxyfuel and air combustion conditions

- The results and experiences gained to be summarized januari 2006 (18 Month)
  → Input to the other partners within the consortium and to continued experimental activities in 100kW and 500 kW test units

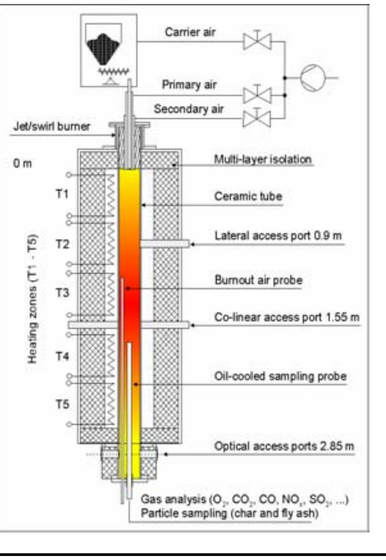
CHALMERS

University Stuttgart

IVD 20kW coal combustion reactor

General caracteristics:

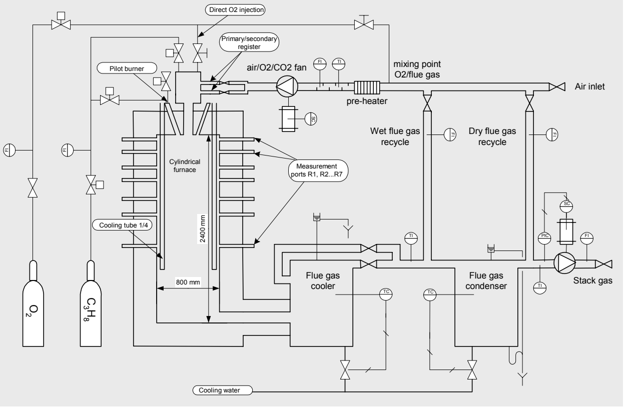
- Furnace: Ceramic tube
- Length of furnace: 2,500 mm
- Diameter: 200 mm
- 5 electrically heated zones (up to 1400°C)
- Synthetic feed gas mixtures – no flue gas recycling
- Measurements performed with oil-cooled probe introduced from the bottom



University Stuttgart

CHALMERS 100 kW oxy-fuel combustion unit

- 100 kW unit
- Specifically designed for Oxyfuel research
- Flue gas recycling applied
- Cylindrical, refractory lined combustion chamber:
  - D = 800 mm
  - H = 2400
- 7x4 measurement ports along reactor sides



University Stuttgart

Test conditions in 20 and 100 kW units

Same test conditions used in both reactors:

- Three different combustion environments
  - Air as reference case
  - OF 21, same volumetric cond. as for air: 21% O_2 and 79% CO_2
  - OF 27, similar temperature cond. as for air: 27% O_2 and 73% CO_2
- Same stoichiometric conditions in all test set-ups
  - $\lambda = 1.15$
- Three different fuels tested:
  - Gas (C_3H_8)
  - Lausitz, lignite
  - Kleinkopje, bituminous coal

CHALMERS

University Stuttgart

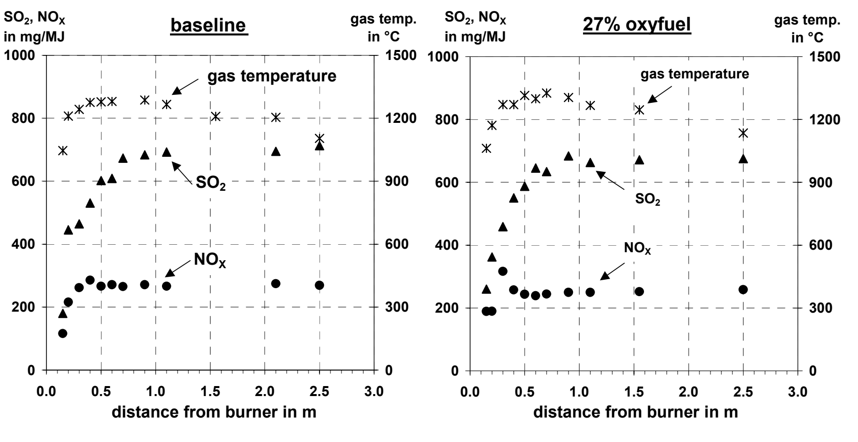
Measurements performed at IVD (Oct 2005)

- Coal combustion characteristics - 20 kW_{th} unit
  - Gas emission behaviour under oxyfuel conditions
  - NO_X reduction potential through staging with oxyfuel
  - NO_X and SO_2 behaviour under simulated flue gas recycling conditions
  - Particle ignition and combustion
    - particle temperatures of three different size fractions: 90 - 150 µm, 150 - 212 µm, 212 - 315 µm
  - Ash and burnout characterisation

CHALMERS

University Stuttgart

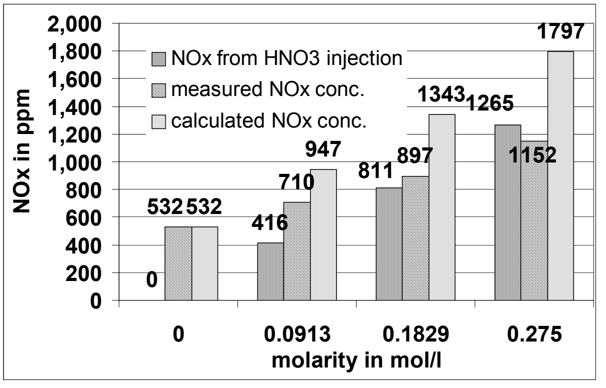
Gas emissions and temperature profiles: air vs. 27% oxyfuel



CHALMERS

University Stuttgart

Effect of HNO_3 injection on NO_X emission

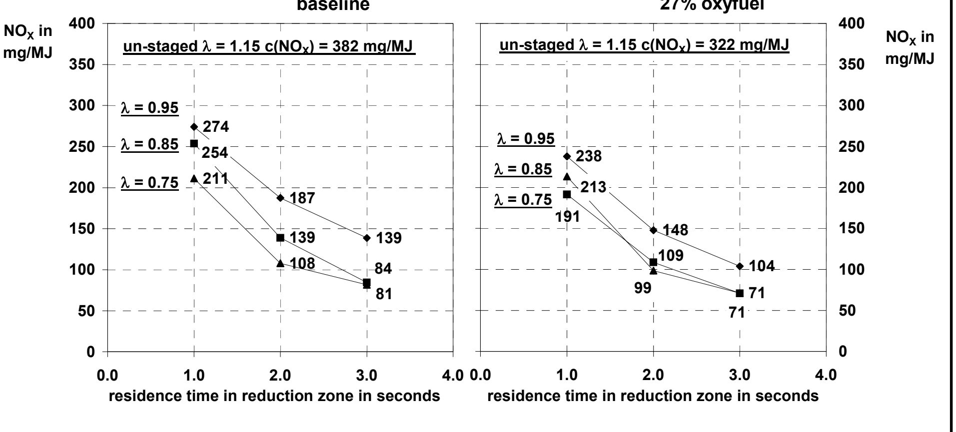


CHALMERS

University Stuttgart

Effect of oxyfuel staging on NO_X emission

Kleinkopje

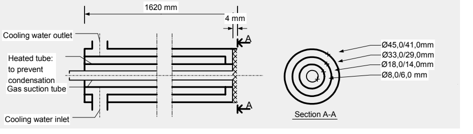


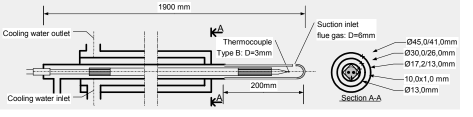
NO_X is given referred to NO_2

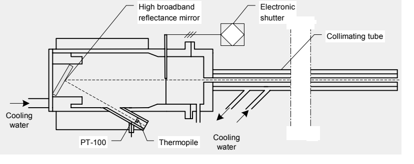
Measurements performed at Chalmers

Flame characteristics:

- Gas concentration profiles
  - O_2, CO, HC, CO_2
  - suction probe/online gas analysis
- Temperature profiles
  - suction pyrometer (thermocouple type B, 2000K)
- Radiation Intensity profiles
  - Narrow angle radiometer (IFRF type)

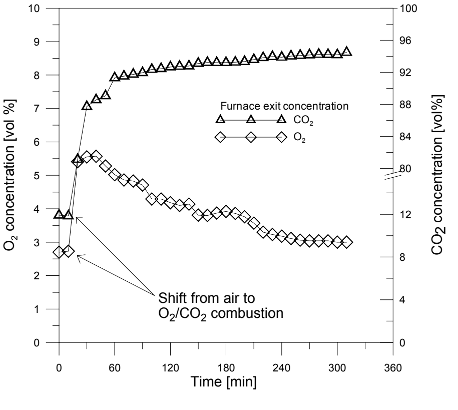






Start-up sequence from air to Oxy-fuel in the Chalmers Unit

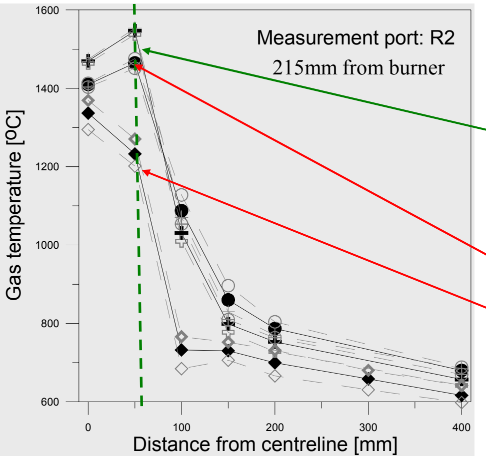
- Stack gas concentrations of O_2 and CO_2
- Start from air to oxy-fuel: stabilized conditions after some 4 to 5 hours
  - 3.0% Oxygen excess reached
  - 94-95% CO_2 in stack gas



CHALMERS

University Stuttgart

Radial temperature profiles: 215 mm from burner inlet

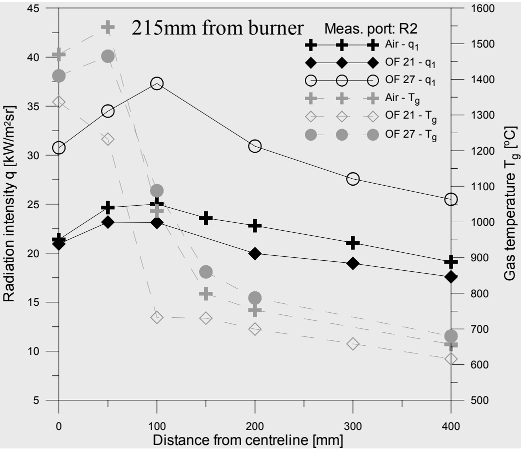


- Profile: centre line to furnace wall
- Reaction zone
- Oxyfuel combustion: temperature control by flue gas recycle rate:
  - ● OF27
  - ❑OF 21

CHALMERS

University Stuttgart

Radial temperature and radiation profiles



- Temperature level of OF 21 case decreases drastically compared to air-fired conditions, but similar radiation intensity.
- OF 27 case similar temperature levels as for air. Radiation intensity from the flame increases 20-30%.
- Change in emissivity

CHALMERS

University Stuttgart

Radiation measurements

- Comparison of measured radiation intensity for Air, OF 21 and OF 27
- Determine
  - flame/gas layer emissivity from measurement data
  - gas emissivity (CO_2, H_2O) with model (Leckner)
- Deviation form expected results?
  - Other effects on radiative properties in oxy-fuel flames?

CHALMERS

University Stuttgart

Mean emissivity

- Radiation received from flame and wall during measurements with hot background

$$q_1 = \int_0^\infty \varepsilon_\lambda R_{\lambda Tg} d\lambda + \varepsilon_b \int_0^\infty (1-\varepsilon_\lambda) R_{\lambda Ts} d\lambda + (1-\varepsilon_b) \int_0^\infty \varepsilon_\lambda (1-\varepsilon_\lambda) R_{\lambda Tg} d\lambda$$

- If ε_b is equal to unity the signal can be rewritten as

$$q_1 = \int_0^\infty \varepsilon_\lambda R_{\lambda Tg} d\lambda + \int_0^\infty (1-\varepsilon_\lambda) R_{\lambda Ts} d\lambda$$

CHALMERS

University Stuttgart

Mean emissivity

- Emissivity is assumed grey:

$$q_1 = \sigma \varepsilon_m T_{mr}^4 + \sigma(1 - \varepsilon_m) T_s^4$$

Schmidt method

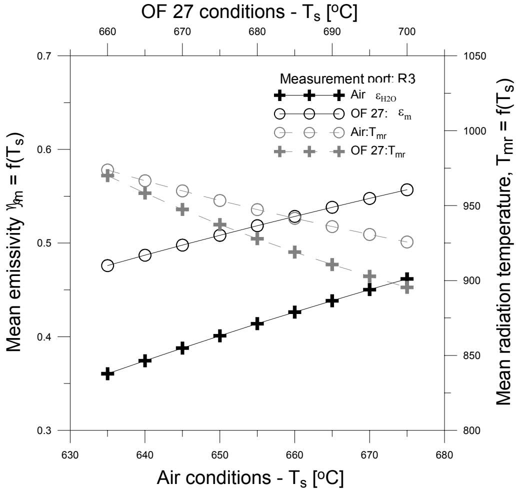
Three separate intensity measurements from

1. The flame and hot furnace wall, q_1,
2. the flame alone with a cold background target, q_2
3. and the hot furnace wall alone q_3

CHALMERS

University Stuttgart

Mean emissivity - furnace cross section



Air case:
- $\varepsilon_m = 0.40$
- $T_s = 650$ºC
- $T_{mr} = 930$ºC

OF 27 case:
- $\varepsilon_m = 0.52$
- $T_s = 680$ºC
- $T_{mr} = 950$ºC

CHALMERS

University Stuttgart

Gas emissivity

- Using available model by (B. Leckner, 1972) to determine the total gas emissivity according to:

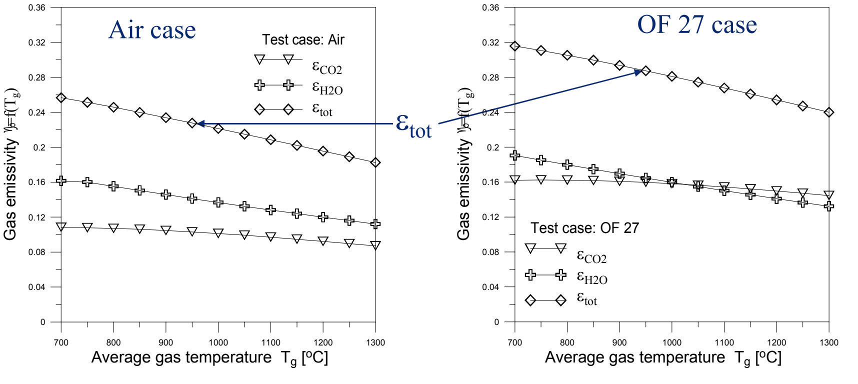
$$\varepsilon_g = \varepsilon_{CO_2} + \varepsilon_{H_2O} - \Delta\varepsilon_{(CO_2+H_2O)}$$

- CO_2 and H_2O emissivities are treated separately
- Band overlap correction term
- Any arbitrary partial pressures of CO_2 and H_2O can be applied in the model.
- Maximum error of 5% for H_2O and 10% for CO_2 emissivities at a temperature above 400 K

CHALMERS

University Stuttgart

Gas emissivity



Test case	p_{CO2}	p_{H2O}	T_s [K]	L [m]
Air	0,10	0,14	928	0,80
OF 27	0,82	0,18	953	0,80

CHALMERS

University Stuttgart

Comparison mean and total gas emissivity

Gas emissivity, ε_g

- Air case: $\varepsilon_g = 0.24$ $T_{mr} = 930°C$ (calculated)
- OF 27 case: $\varepsilon_g = 0.30$ $T_{mr} = 950°C$ (calculated)

Mean emissivity, ε_m

- Air case: $\varepsilon_m = 0.40$ $T_s = 650$ °C (measured)
- OF 27 case: ε_m 0.52 $T_s = 680°C$ (measured)

CHALMERS

University Stuttgart

Conclusions from gas fired tests

Compared to reference tests with air in the 100 kW unit:

- The temperature level of OF 21 case drops drastically and leads to a delayed burn-out as detected from HC and O2-profiles
- The OF 27 case shows similar temperature levels, which together with an increase in O_2-concentration in the recycled feed gas results in similar combustion intensity and burn-out behavior
- The radiation intensity of the OF 27 flame increases with about 20-30% despite similar temperature profiles.
- Increased emissivity not only due to the increased band radiation from CO_2. The soot formation for various oxy-fuel conditions and fuels need to be studied in detail for use in RT-modeling.

CHALMERS

University Stuttgart

Conclusions from coal fired tests

- Gas emissions:
  - Small decrease in NO_X emission rate for OF 27 without flue gas recycle
  - No difference in SO_2 generation
  - Neglegleble CO emissions, identical for air and oxyfuel case
- Oxyfuel staging:
  - Reduction of NO_X emission rate equal or better for oxyfuel case compared to air case
- Ignition behavior:
  - Particle ignition and burnout is accelerated with higher oxyfuel concentrations
  - Temperatures reached for 27% oxyfuel are comparable to those for air
- Ash quality:
  - Little change in oxyfuel ashes compared to ashes from air combustion

CHALMERS

University Stuttgart

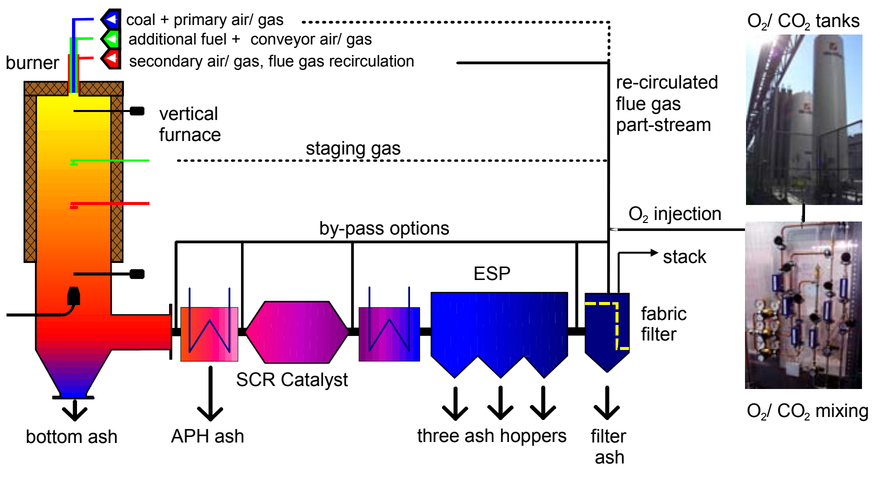
Up-coming activities within the ENCAP experimental programme: 100 kW and 500 kW units

1. Burner concepts and design
   - burner adaptation
   - start-up/ shut-down procedures
2. Radiation characteristics
   -radiation measurements coal-firing
3. Burnout and emission behavior
   - ash sampling
   - re-circulation vs. NO_X/SO_2 behavior
4. Slagging, fouling and fly ash behavior
   - deposition behavior of the coals
   - particle load behavior

CHALMERS

University Stuttgart

IVD 0.5 MW_{th} unit modified for oxyfuel operation



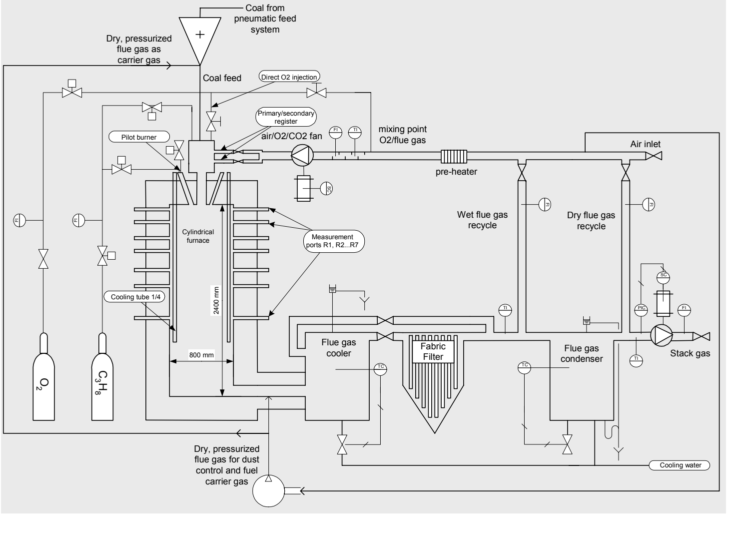
CHALMERS

University Stuttgart

CHALMERS 100 kW_{th} unit modified for oxy-coal operation

Modified for coal tests summer 2005

Initial tests with dried lignite (Lausitz) performed autumn 2005



Oxyfuel pilot testing in phase 2 of ENCAP

- The ”Oxyfuel boiler technology” subproject will nominate two candidates for pilot testing in phase 2
  - Phase 2: August 2006-March 2009
- 30 MW_{th} Oxyfuel PF plant
  - New-built plant located next to the Schwarze Pumpe power station
  - Investment decision taken by Vattenfall in May 2005
- 1 MW_{th} Oxyfuel CFB plant
  - Based on modifications to an existing test-facility
- Decision on which of the pilot options that will be financed within the ENCAP project will be taken the next few months

Inaugural Workshop

International Oxy-Combustion Research Network

Vattenfall Europe Mining and Generation AG Head Office
Cottbus, Germany

29th and 30th November 2005

PRESENTATION - 07

Development in Oxy-Coal Combustion Boiler: A View from Boiler Manufacturer

by:

Timo Hyppänen
Foster Wheeler Oy, Finland

This page is intentionally left blank

Timo Hyppänen, Arto Hotta
Inaugural Workshop on OxyFuel Combustion
Cottbus, Germany
November 29.-30., 2005

FOSTER WHEELER

Development in Oxy-coal Combustion Boiler: A View from Boiler Manufacturer

Inaugural Workshop on OxyFuel Combustion, Cottbus, November 29.-30., 2005

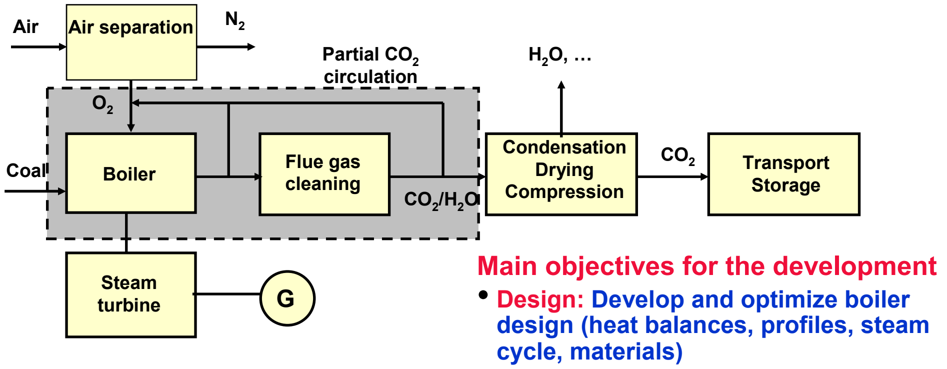
Outline of presentation

- Oxycombustion in PC boilers
  - Plant optimization
  - Burner design in oxycombustion
  - Boiler design in oxycombustion
- Oxycombustion in CFB boilers
  - R&D
  - Process performance in oxycombustion
  - Boiler design in oxycombustion
  - Commercialization pathway

FOSTER WHEELER

Role of the boiler in oxycombustion plant

Inaugural Workshop on OxyFuel Combustion, Cottbus, November 29.-30., 2005



Main objectives for the development

- **Design:** Develop and optimize boiler design (heat balances, profiles, steam cycle, materials)
- **Performance:** Efficiency, combustion, emissions, availability
- **Cost:** Capital, operating and maintenance

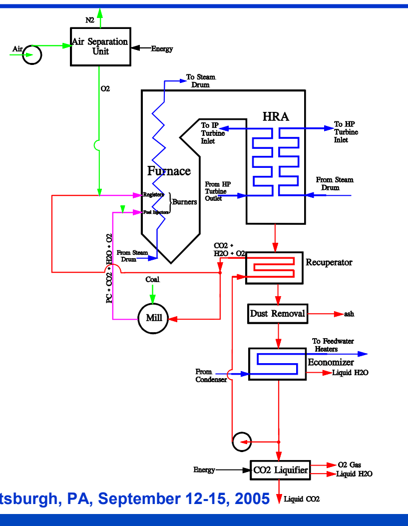
FOSTER WHEELER

OXYPC STUDY

Inaugural Workshop on OxyFuel Combustion, Cottbus, November 29.-30., 2005

- **System:** Optimize plant design to maximize overall efficiency
- **Burners:** Optimize design to ensure stable ignition, safe operation, and minimize NOx
- **Furnace and HRA:** Optimize location of burners, ports, and internal radiant surfaces
- **Economics:** Compare cost of electricity generation to other CO_2 capture technologies

➢ Reference: Subcritical 460MW HV Bituminous



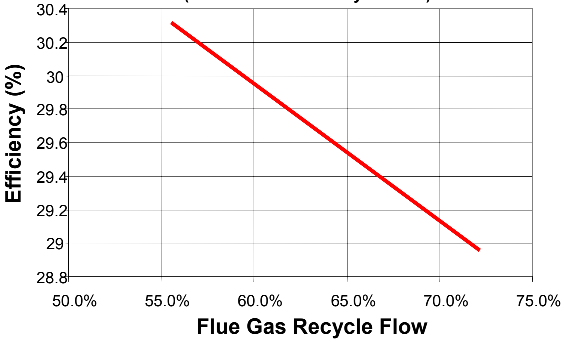
Ref.: Selzer, Fan & Fout, 22nd Annual Pittsburgh Coal Conference Pittsburgh, PA, September 12-15, 2005

FOSTER WHEELER

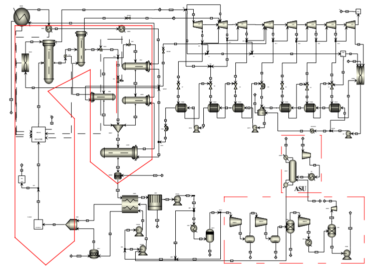
OXYPC
Plant Optimization

Net Cycle Efficiency Vs. Flue Gas Recycle Flow

(Air-Fired PC Efficiency = 36.7%)



O2-Fired PC System Model (Aspen-Plus)



- Cryogenic ASU
- Subcritical steam cycle

OXYPC
Burner design

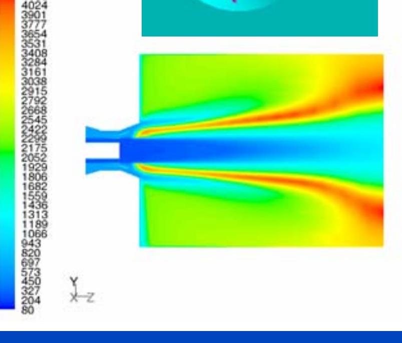
Inaugural Workshop on OxyFuel Combustion, Cottbus, November 29.-30., 2005

Burner design objectives

- Low NOx
- Stable ignition
- Safe operation
- Coal burnout

Optimization variables

- Oxygen/recirc. gas ratios in primary and secondary gas streams
- Swirl and velocity in prim./sec. gases
- Over fire gas

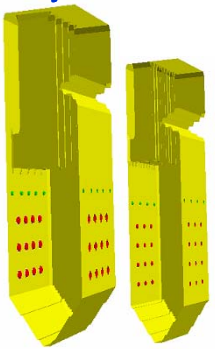


FOSTER WHEELER

OXYPC
Furnace and HRA design

Inaugural Workshop on OxyFuel Combustion, Cottbus, November 29.-30., 2005

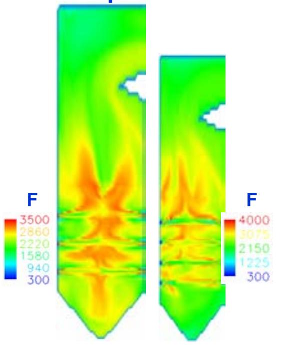
Boiler Design
Recycle flow 56 %



Air-Fired PC O2-Fired PC

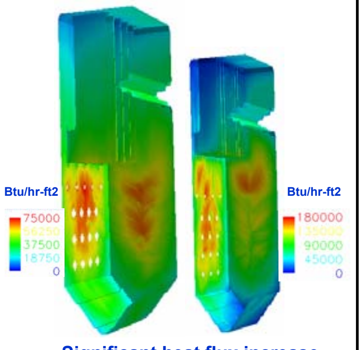
65% of Air PC Surface Area
45% of the volume

Furnace Gas Temperature



Increased burnout, lower NOx

Furnace Wall Heat Flux

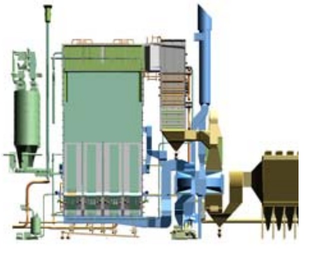


- Significant heat flux increase due to higher T, H_2O, CO_2
- Waterwall material upgraded from C.S. to T91

FOSTER WHEELER

OXYCFB

Inaugural Workshop on OxyFuel Combustion, Cottbus, November 29.-30., 2005

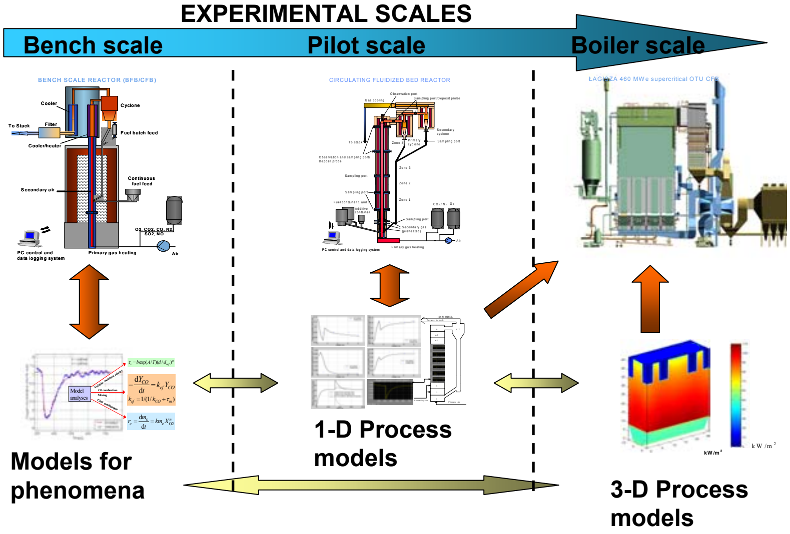


- The CFB advantages exist in CFB oxycombustion
- Multi-fuel capability (coal, petroleum coke, lignites etc.)
- SOx and NOx reduction without scrubbers
- Dual-firing Capability: Design CFB boiler for air-firing and oxy-firing.
- Balancing of temperature levels by fluidized bed mixing -> Potential for high O_2 contents -> Opportunities to make significant size reductions and high boiler efficiencies.
- FW CFB heat surface options available for high O_2 contents.

FOSTER WHEELER

OXYCFB testing and development
Combustion process

Inaugural Workshop on OxyFuel Combustion, Cottbus, November 29.-30., 2005

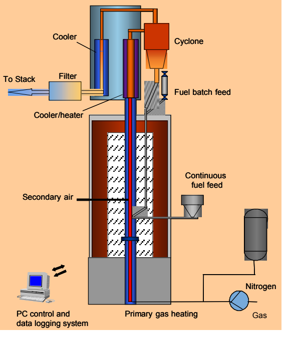


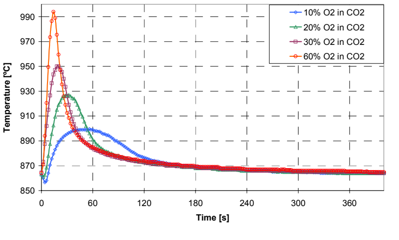
OXYCFB boiler performance
Combustion process – bench scale tests

Inaugural Workshop on OxyFuel Combustion, Cottbus, November 29.-30., 2005

Bench scale testing

- VTT, Technical Research Centre of Finland





Effect of O_2/CO_2 atmosphere on

- Emissions
  - NOx
  - CO
  - SO_2/Sorbent
- Combustion
- Materials

FOSTER WHEELER

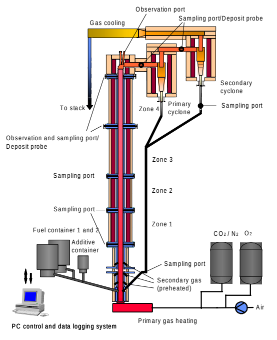
OXYCFB boiler performance
Combustion process – pilot testing

Inaugural Workshop on OxyFuel Combustion, Cottbus, November 29.-30., 2005

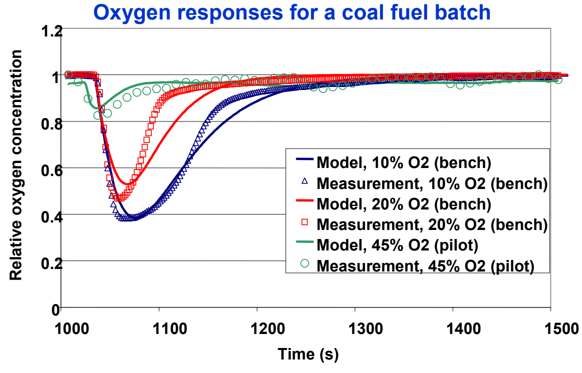
Pilot scale testing

- VTT, Technical Research Centre of Finland

CIRCULATING FLUIDIZED BED REACTOR



Oxygen responses for a coal fuel batch



Effect of Oxycombustion →

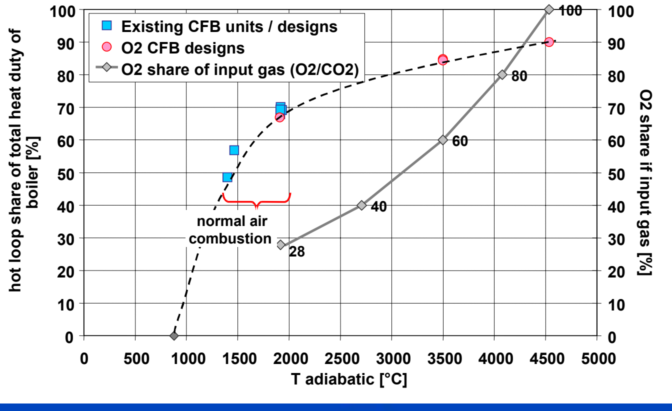
- Emissions
- Combustion profiles
- Temperature/heat duty profiles
- Materials

FOSTER WHEELER

OXYCFB
Boiler design

Inaugural Workshop on OxyFuel Combustion, Cottbus, November 29.-30., 2005

Effect of O2 concentration on boiler heat balance.



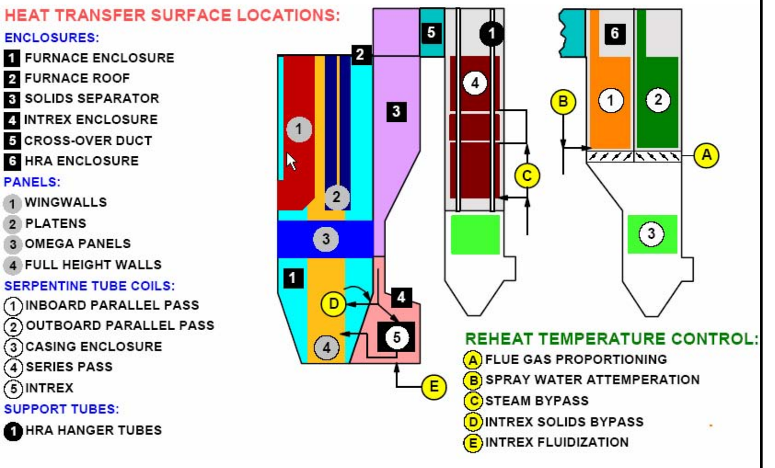
FOSTER WHEELER

OXYCFB
Boiler design options

Inaugural Workshop on OxyFuel Combustion, Cottbus, November 29.-30., 2005

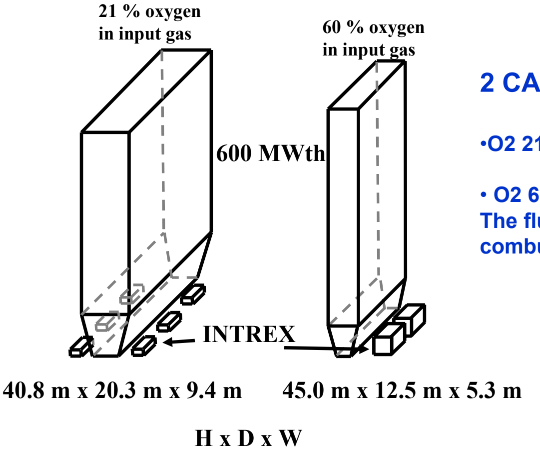
Boiler design

- Heat balances for varying loads/fuel qualities
- Optimisation of oxygen/recirc. gases
- Development of heat surface configurations



OXYCFB
Effect of oxygen enrichment, a preliminary study

Inaugural Workshop on OxyFuel Combustion, Cottbus, November 29.-30., 2005



2 CASES, 600 MWth:

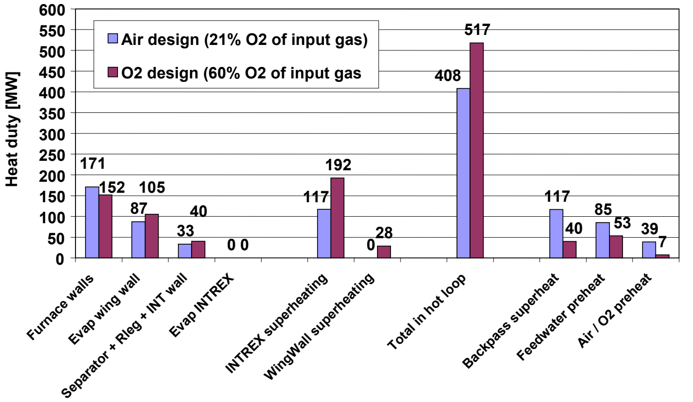
•O2 21 %: Normal combustion with air.

• O2 60 %: 60 % of gas fed to the CFB is O2. The flue gas flow rate is 40 % from normal air combustion. Total volume reduced to 38 %.

OXYCFB
Oxygen enrichment

Inaugural Workshop on OxyFuel Combustion, Cottbus, November 29.-30., 2005

Heat duties in the two cases

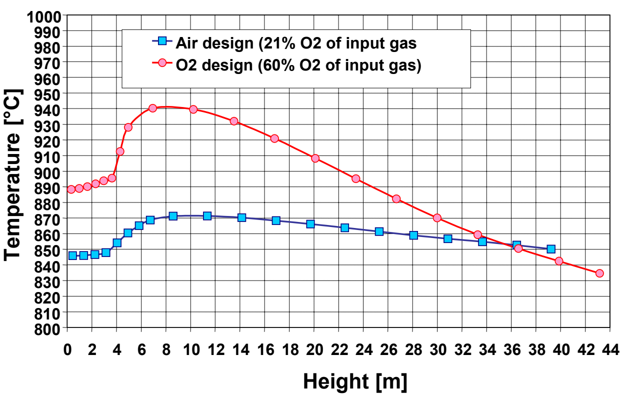


FOSTER WHEELER

OXYCFB
Oxygen enrichment

Inaugural Workshop on OxyFuel Combustion, Cottbus, November 29.-30., 2005

Vertical temperature profiles in the furnace in the two cases

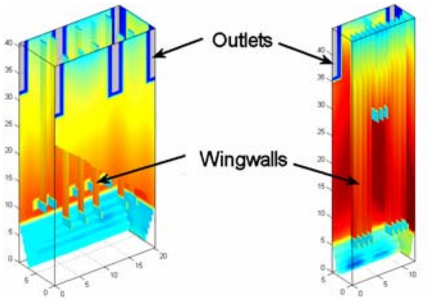


FOSTER WHEELER

OXYCFB

Effect of oxygen enrichment, a preliminary 3-D study

21 % O2 | 60 % O2



40.8 m x 20.3 m x 9.4 m | 45.0 m x 12.5 m x 5.3 m

2 CASES, 600 MWth:

- O2 21 %: Air combustion, O_2 = 21 %.
- O2 60 %: 60 % of gas fed to the CFB is O_2. The fluegas flow is 40 % from normal air combustion. Total volume reduced to 38 %.

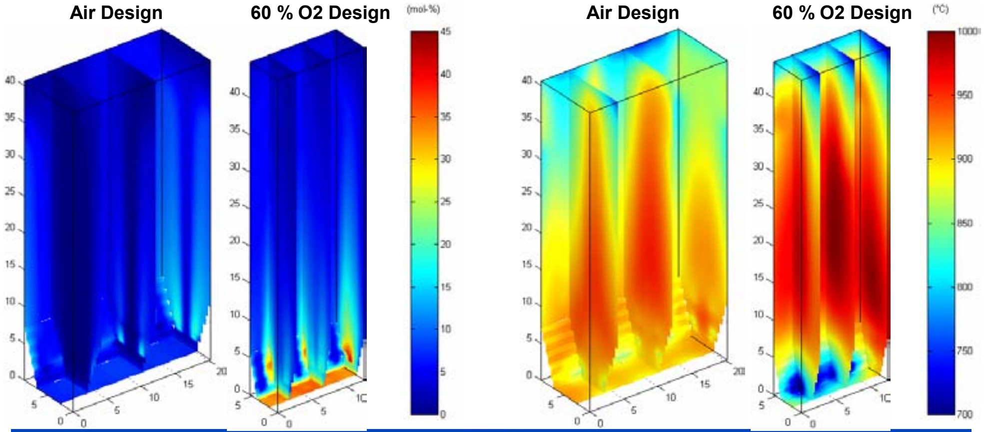
OxyCFB boiler performance

Combustion process, 3-D study

Inaugural Workshop on OxyFuel Combustion, Cottbus, November 29.-30., 2005

Oxygen concentration | Temperature

Air Design | 60 % O2 Design | Air Design | 60 % O2 Design



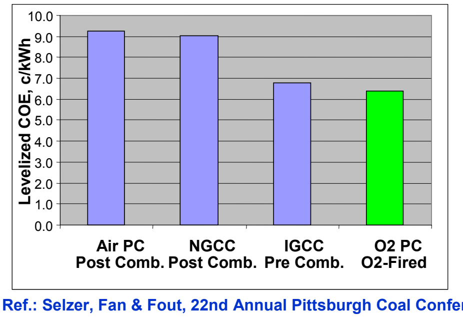
OXYCOMBUSTION
Economics

- COE increases from 4.61 to 6.41 ¢/kWh
- MC = 21.4 $/tonne

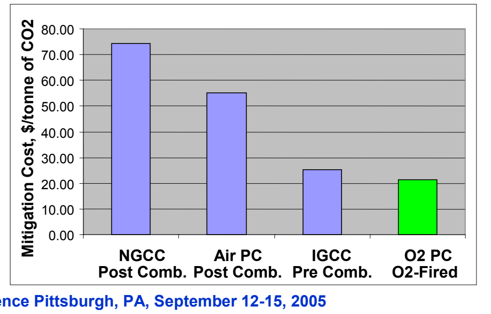
Capital costs

- FGD –10 %
- ASU + 20 %
- CO_2 + 7 %
- Overall + 18 %

Cost of Electricity



Mitigation cost



Ref.: Selzer, Fan & Fout, 22nd Annual Pittsburgh Coal Conference Pittsburgh, PA, September 12-15, 2005

FOSTER WHEELER

Oxycombustion CFB – Commercialization Pathway

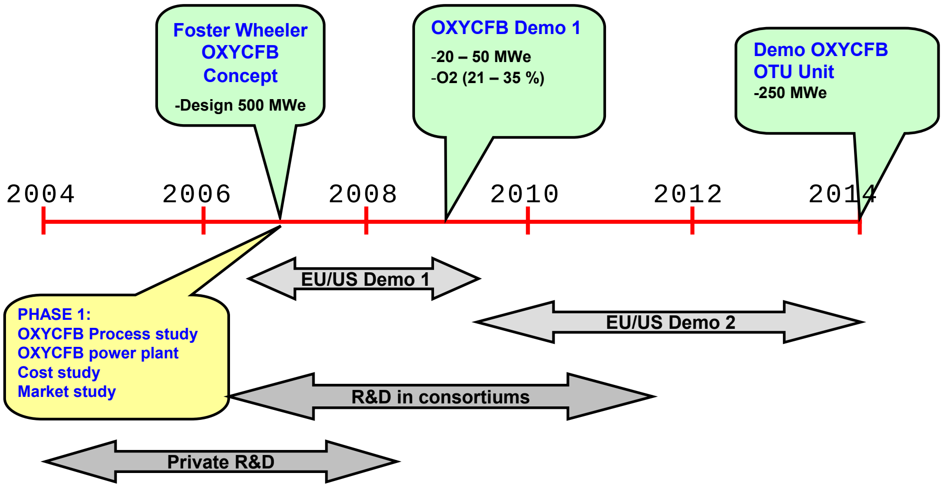
Inaugural Workshop on OxyFuel Combustion, Cottbus, November 29.-30., 2005

- Partnerships for R&D and commercial demonstrations
- R&D (2003 ->)
- Small scale pilot testing (2005 ->)
- Large scale (1 - 10 MWt) oxycombustion CFB pilot plant (2006 – 2008)
- Small scale (25 MWe) demonstration plant in US / Europe (2008 – 2010)
- Large scale (250 MWe) demonstration plant in US / Europe (2010 – 2015)
- First commercial sale (100 – 400 MWe) (2013 – 2016)

FOSTER WHEELER

OXYCFB
Roadmap/OxyCFB development

Inaugural Workshop on OxyFuel Combustion, Cottbus, November 29.-30., 2005



FOSTER WHEELER

OXYCOMBUSTION
SUMMARY

Inaugural Workshop on OxyFuel Combustion, Cottbus, November 29.-30., 2005

- **Both PC and CFB technology are feasible solutions for oxycombustion**
- **Further development and optimisation will provide more comprehensive picture of the role of oxycombustion in reducing CO_2.**
  - **fuels, capacities, steam cycles, overall plant options, new designs/concepts**
- **Experimental research and demonstration of oxycombustion needed**
  - **reduce risks**
  - **refine the prediction and design methods and tools for boiler designs and performance predictions**
- **Demonstration of oxycombustion**
  - **small risk in combustion process especially for lower oxygen concentrations in retrofits**

FOSTER WHEELER

This page is intentionally left blank

Inaugural Workshop

International Oxy-Combustion Research Network

Vattenfall Europe Mining and Generation AG Head Office
Cottbus, Germany

29th and 30th November 2005

PRESENTATION - 08

Air Liquide's Air Separation Units: Mastering Design and Operations

by:

Guillaume de Souza
Air Liquide, France

This page is intentionally left blank

IEA GREENHOUSE GAS R&D PROGRAMME

AIR LIQUIDE

IEA GREENHOUSE GAS R&D PROGRAMME

AIR LIQUIDE

OXYCOMBUSTION, 5 key points for Design and Operation:

1. Very Large ASU Design and Experience
2. Energy Saving Optimization
3. Potential Integration within Customer Process
4. Availability Expertise
5. Direct CO_2 Compression for storage

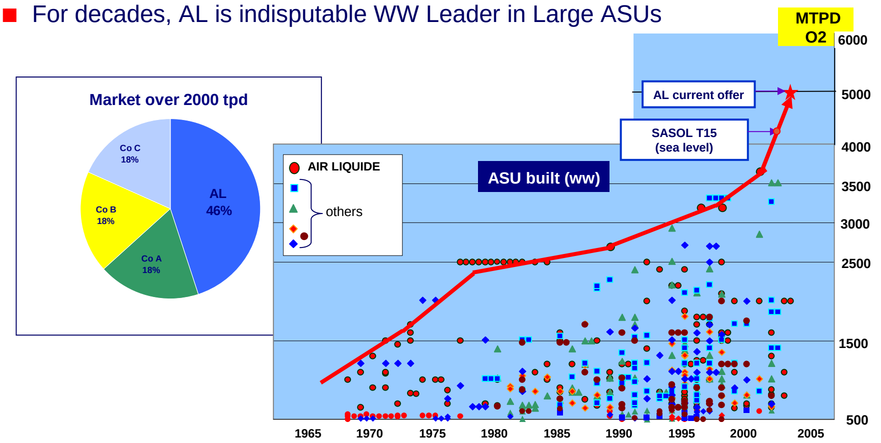
Confidential - Property of AIR LIQUIDE
Communication to parties not member of AIR LIQUIDE is prohibited

VERY LARGE ASUs

Large ASUs: AL Clear Front Runner in Technology

AIR LIQUIDE

- Technical Boundaries of Cryogenics are far to be reached
  - Usual Size Effect Figures remain valid (savings increase faster than costs)
  - 5 000 mtpd is already in AL portfolio (all technical issues addressed)
  - Larger ASUs [7000 tpd] are already planned
- For decades, AL is indisputable WW Leader in Large ASUs



Confidential - Property of AIR LIQUIDE
Communication to parties not member of AIR LIQUIDE is prohibited

The world leader in industrial and medical gases 3

VERY LARGE ASUs

Largest ASU ever built : Sasol (RSA) T15

AIR LIQUIDE

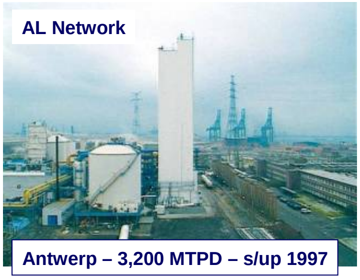
(*) max run 4000 MTPD, atm pressure: 0,85 bar

Confidential - Property of AIR LIQUIDE
Communication to parties not member of AIR LIQUIDE is prohibited

The world leader in industrial and medical gases 4

AIR LIQUIDE : Wide Experience Basis

AIR LIQUIDE



Energy versus Investment Optimization

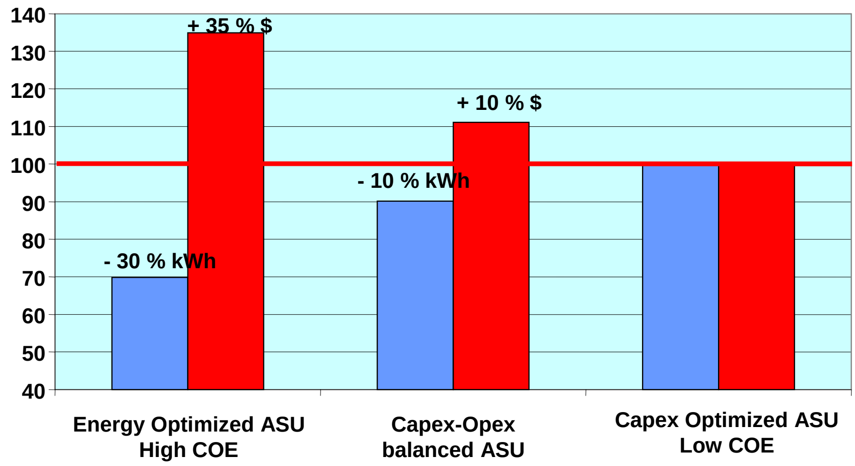
AIR LIQUIDE

Depending on the context AL can design ASUs for CAPEX vs OPEX optimization

Energy Cost	High		Low
ASU Specific Energy (W/m³ O2)	Low	+/- 20 %	Higher
ASU Investment Cost ($)	Higher	+/- 20 %	Low
Technical Leverage (ex.)	Isothermal Machines Low Press. Cycle Low Press. Drop Design		Isentropic Machines Compact Design Heat Losses
Examples	 High Yield	 Capex/Opex	 Low Capex

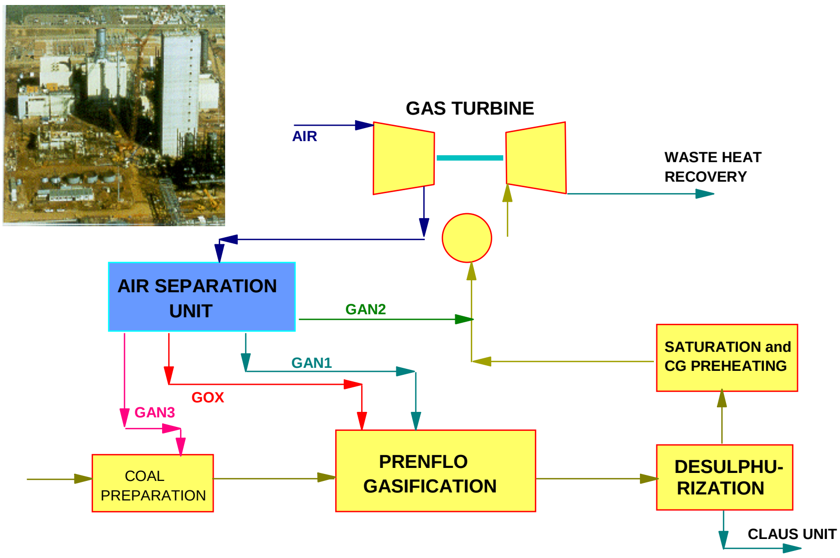
Energy versus Investment Optimization

AIR LIQUIDE



100% Integration Example : ElcoGas Gasification

AIR LIQUIDE



Integration Capabilities

ELCOGAS Project : AIR LIQUIDE Scope of Work

AIR LIQUIDE

Air Liquide was awarded a Turn Key Contract in early 93

- ASU capacity:
  - air processed 300 000 Nm3/h
  - oxygen supply 70 000 Nm3/h
- ASU to be fully integrated:
  - air intake to ASU from GT
  - nitrogen injection in GT for syngas dilution
- ASU to be flexible:
  - air intake floating pressure (loads from 50 to 100%) upon GT load
  - fixed minimum pressure for products supply
  - change load capability: minimum 3% per minute

The world leader in industrial and medical gases 9

Availability & Reliability

AIR LIQUIDE : Availability & Reliability Excellence

AIR LIQUIDE

Availability 2004(*):
ASU1 = 99,67%
ASU2 = 99,72%

SARLUX – 2 x 2300 MTPD – s/u 1998

ISAB : 2 x 1850 MTPD s/u 1994

Availability 2004(*):
ASU1 = 99,79%
ASU2 = 99,98%

(*) ratio between the quantity produced and the requested quantity, before back-up (stand alone units), planned maintenance excluded

Towards the Best Availability, AL offers its :

- Engineering Know How in Reliability Calculation tools
  + Exclusive in house reliability Data Base
- Operation Excellence thanks to its 200 ASUs operated worldwide

Confidential - Property of AIR LIQUIDE
Communication to parties not member of AIR LIQUIDE is prohibited

The world leader in industrial and medical gases 10

This page is intentionally left blank

Inaugural Workshop

International Oxy-Combustion Research Network

Vattenfall Europe Mining and Generation AG Head Office
Cottbus, Germany

29th and 30th November 2005

PRESENTATION - 09

Oxy-Combustion for CO_2 Capture in Pulverized Coal Boilers

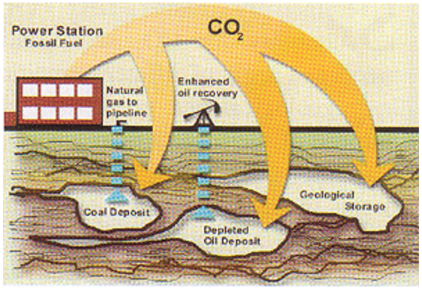
by:

Guillaume de Smedt
Air Liquide, France

This page is intentionally left blank

AIR LIQUIDE

Oxy-combustion for CO_2 capture in pulverized coal boilers (PC-OC)

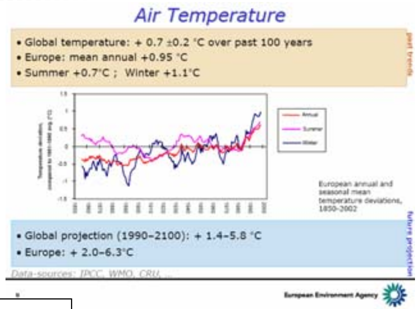


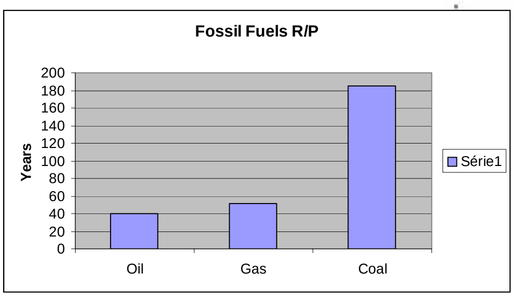
AIR LIQUIDE

Key Drivers

- Climate change
  - ✓ Awareness raising
  - ✓ Ambitious targets “Factor 4”

  Need to reduce GHG emissions



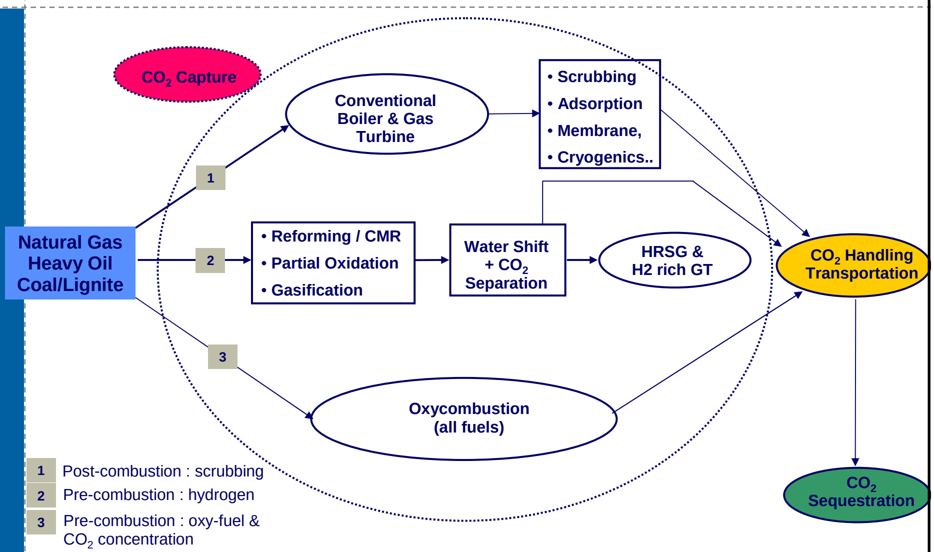


- Coal role in energy mix
- Large availability in some areas

  Need technologies for clean coal use

Clean fossil fuel technology pathways

AIR LIQUIDE



Multiple pathways for multiple applications & situations

Oxy-combustion Developments

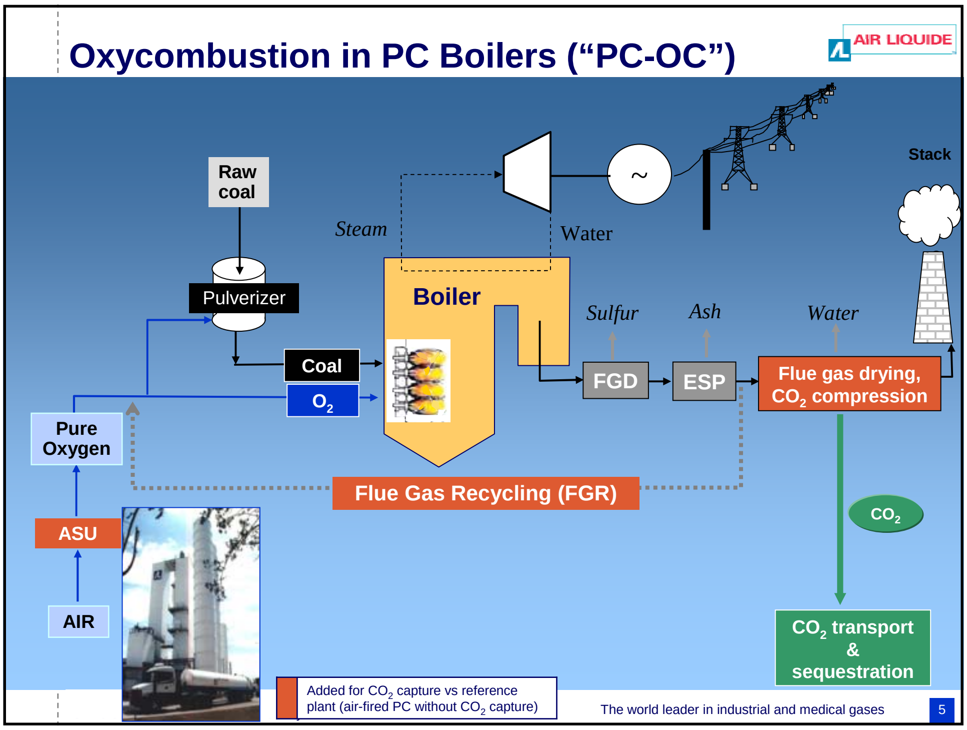
AIR LIQUIDE

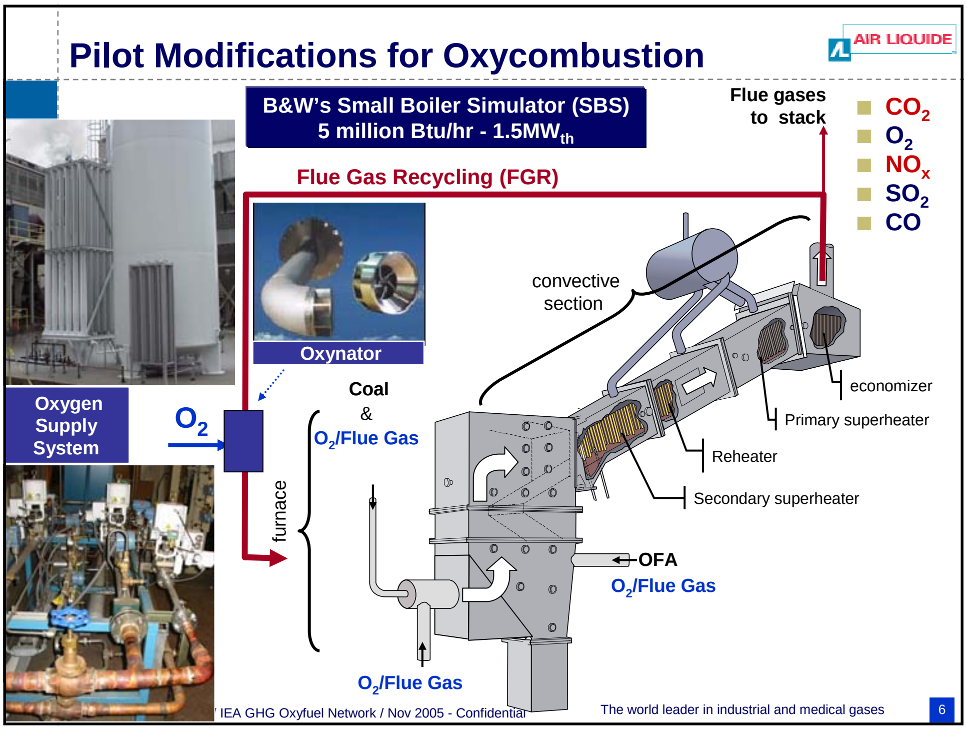
- Years of Industrial Experience
- Large Pilot Facilities
- Several Projects covering most Fuels
- Direct Oxy and FGR

Natural Gas

Liquid/HFO

Coal/Lignite


Oxycombustion in PC Boilers ("PC-OC")
AIR LIQUIDE
Raw coal
Pulverizer
Steam
Water
Boiler
Stack
Sulfur
Ash
Water
Coal
O_2
FGD
ESP
Flue gas drying, CO_2 compression
Pure Oxygen
Flue Gas Recycling (FGR)
ASU
AIR
CO_2
CO_2 transport & sequestration
Added for CO_2 capture vs reference plant (air-fired PC without CO_2 capture)
The world leader in industrial and medical gases
5

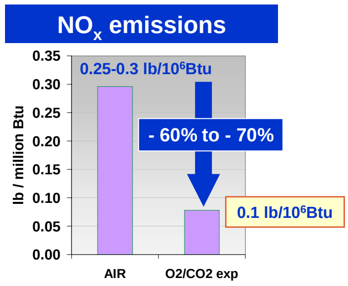

Pilot Modifications for Oxycombustion
AIR LIQUIDE
B&W's Small Boiler Simulator (SBS)
5 million Btu/hr - 1.5MW$_{th}$
Flue gases to stack
CO_2
O_2
NO_x
SO_2
CO
Flue Gas Recycling (FGR)
convective section
Oxynator
Oxygen Supply System
O_2
Coal & O_2/Flue Gas
furnace
economizer
Primary superheater
Reheater
Secondary superheater
OFA
O_2/Flue Gas
O_2/Flue Gas
IEA GHG Oxyfuel Network / Nov 2005 - Confidential
The world leader in industrial and medical gases
6

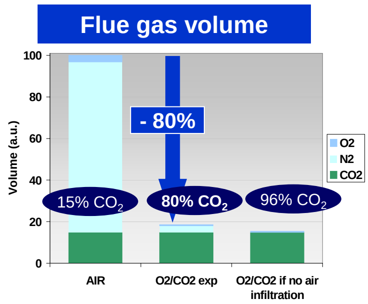
Pilot tests Results

AIR LIQUIDE

- Successful demonstration and process characterization

  - **Technical feasibility demonstrated**: Safe and smooth conversion from air-fired to O_2/Flue Gas operation
  - **Flue gas volume**: reduced by **80%** ⇒ Reduced cost of CO_2 purification
  - **CO_2 content** in Flue Gases: increased from 15% in air-fired conditions **up to 80% in oxy-combustion**.
  - **NO_x emission**: reduced by **60 to 70%**
  - **Heat Transfer Performances**: similar in air and oxy firing ⇒ retrofit application ok

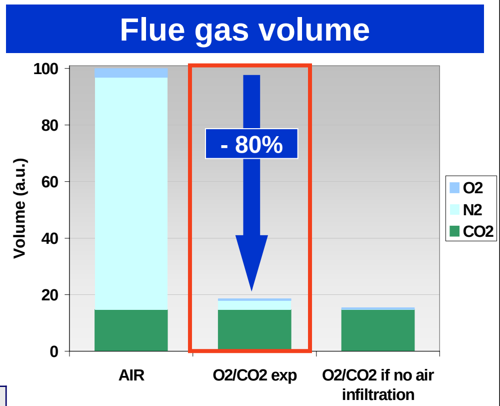




Tests Results: Flue Gas Volume and Content

AIR LIQUIDE

- Flue Gas Volume Reduced by **80%**
- CO_2 concentration increased from 15% in air-firing to 80% in O_2-firing



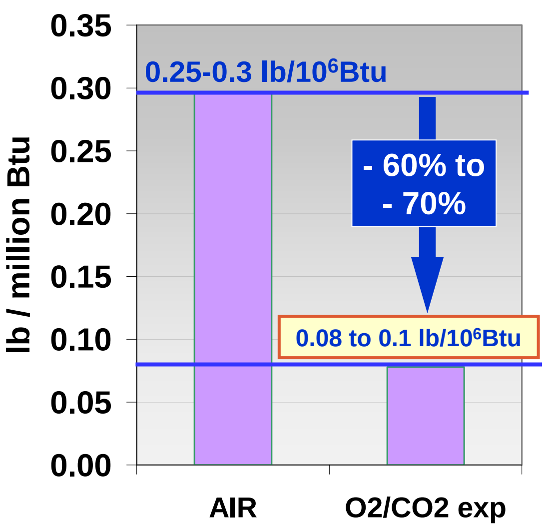
a.u. = Arbitrary Units

	AIR	O_2/CO_2 exp (5% air infiltration)	O_2/CO_2 without air infiltration
O_2	3%	3%	3%
CO_2	15%	80%	96%
N_2	82%	17%	1%
Volume	100 a.u.	19 a.u.	16 a.u.

Flue gas composition

Tests Results: NO_x Emission

AIR LIQUIDE



- NO_x emission reduced by up to 70% vs air-firing

HOW?

- NO "reburning" (FGR)
  NO ⇒ N_2
- Control of temperature:
  - Higher devolatilization temp. via **O_2 local enrichment**:
    Fuel-NO_x ↘
  - Control of flame peak temperature:
    Thermal NO_x ↘

Conclusions of Experimental Tests

AIR LIQUIDE

- **Technical Feasibility of the Oxycombustion Process**
  - An existing pilot-scale boiler has been modified to enable oxygen combustion in flue gas recycle
  - The **feasibility** of the oxycombustion process has been **demonstrated on a pilot-scale** ($1.5MW_{th}$) unit designed for development of industrial boiler and burner technologies.
  - A **safe and smooth transition** from air to oxy-combustion has been achieved
  - Improved know-how on O_2 management in PP environment, operability & safety procedures
- **CO_2 Capture Capability**
  - The **CO_2 in flue gases has been concentrated to 80%** (vol. Dry basis) vs 15% in air-firing. Additional developments are likely to further reduce the air infiltrations
  - The Flue Gas Volume has been **reduced by 80%** vs air-fired operation enabling **cost effective removal of other pollutants** if needed (depending on CO_2 purity requirement)

ns of Experimental TestsConclusio

AIR LIQUIDE

- **Heat Transfer Characteristics**
  - Boiler exit gas temperatures and FEGT measurements indicate **similar heat temperature profiles**.
  - **Flame emissivity** is similar in air and (dry) O_2-firing operation
  - Flamme T controlled by FGR dilution
  - Combustion efficiency controlled via ad-hoc selection of O_2 content in each oxidant stream
  - ⇒ No adverse side effects on boiler performance is anticipated.
- **NO_x emissions**
  - NO_x emissions have been **reduced by up to 70%** vs staged air-firing operation: reduced need for SCR

G. De Smedt – Cottbus / IEA GHG Oxyfuel Network / Nov 2005 - Confidential

The world leader in industrial and medical gases 11

Conclusions & next steps

AIR LIQUIDE

- Oxy-coal combustion tests
  - No “show stopper” encountered regarding larger scale plants
  - Operational experience gained
  - Inherent NO_X reduction
- O_2/CO_2 combustion allows retrofit of existing PP
- New units would allow better management of air inlet
- New PP
  - CO_2 capture plants
  - “Capture-ready” plants

    ……… to be ready for capture
- Economics show oxy-coal is competitive
- Next steps
  - Detailed engineering studies
  - Participation to large scale demo plant

G. De Smedt – Cottbus / IEA GHG Oxyfuel Network / Nov 2005 - Confidential

The world leader in industrial and medical gases 12

AIR LIQUIDE™

Thank you for your attention

Questions?

guillaume.de-smedt@airliquide.com

This page is intentionally left blank

Inaugural Workshop

International Oxy-Combustion Research Network

Vattenfall Europe Mining and Generation AG Head Office
Cottbus, Germany

29th and 30th November 2005

PRESENTATION - 10

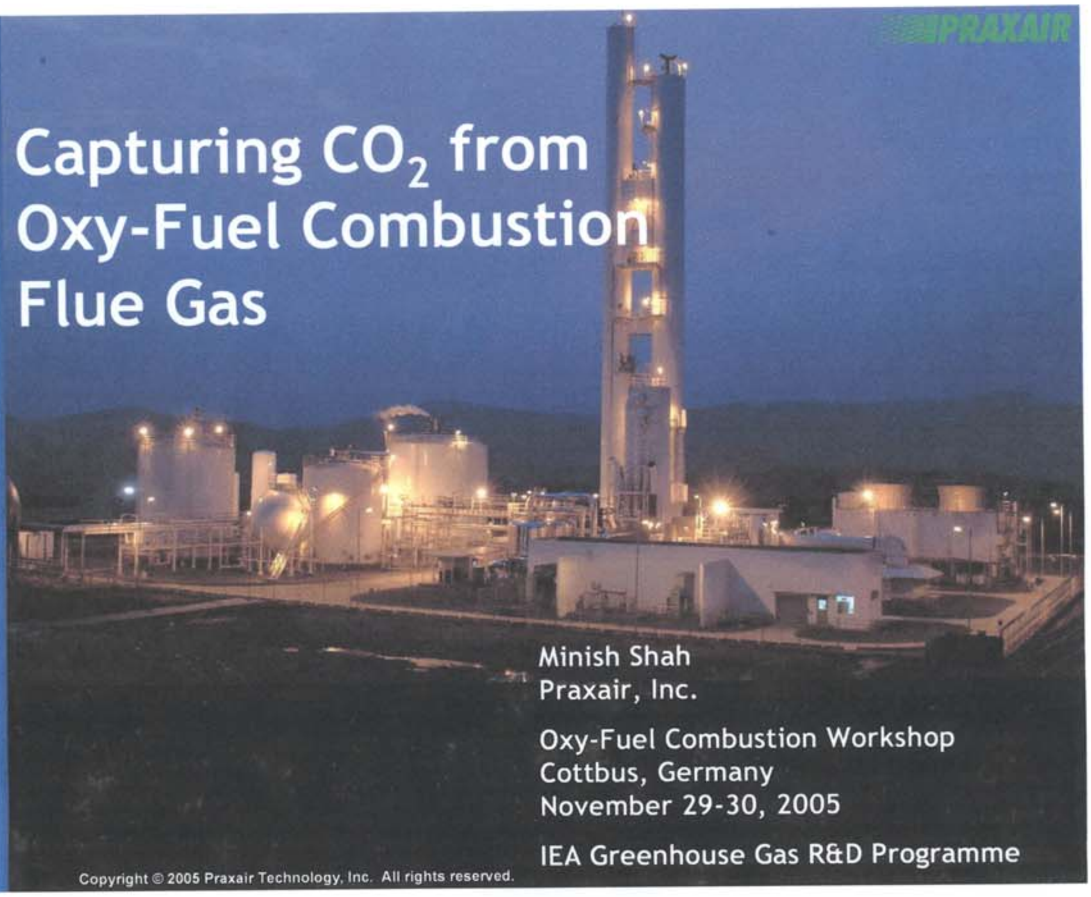
Capturing CO_2 from Oxy-Fuel Combustion Flue Gas

by:

Minish Shah
Praxair, USA

IEA GREENHOUSE GAS R&D PROGRAMME

This page is intentionally left blank



Capturing CO_2 from Oxy-Fuel Combustion Flue Gas

Minish Shah
Praxair, Inc.

Oxy-Fuel Combustion Workshop
Cottbus, Germany
November 29-30, 2005

IEA Greenhouse Gas R&D Programme

PRAXAIR

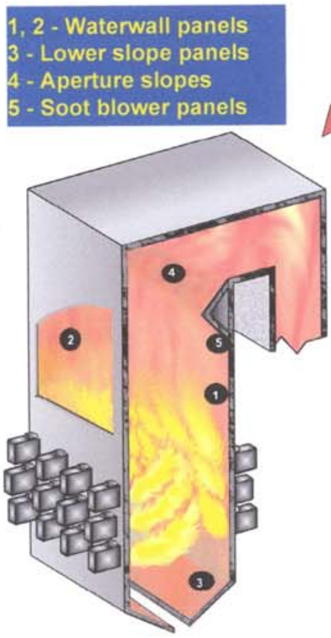
Praxair Gas Separations Technologies for Oxy-Fuel Combustion

PRAXAIR

- **VPSA Oxygen**
  - Up to 250 tpd from a single unit
- **Cryogenic Oxygen**
  - Built plants up to 3000 tpd
  - Larger plants being designed
- **CO_2**
  - CO_2 capacity > 15,000 tpd
  - Leader in 80% of markets served
  - Purification experience with wide range of sources (NH_3, H_2, NG, EtOH, Combustion)

2

Praxair Applications Technologies for Oxy-Fuel Combustion



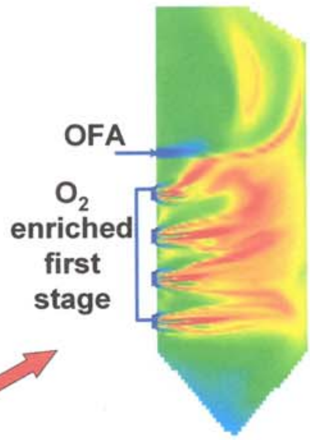
- Laser weld overlay
  - Proven solutions for corrosion and erosion due to low-NOx burners

- Coatings for steam turbines
- Oxy-fuel burners for in-furnace FGR

3

Praxair Experience in Oxy-Fuel Combustion

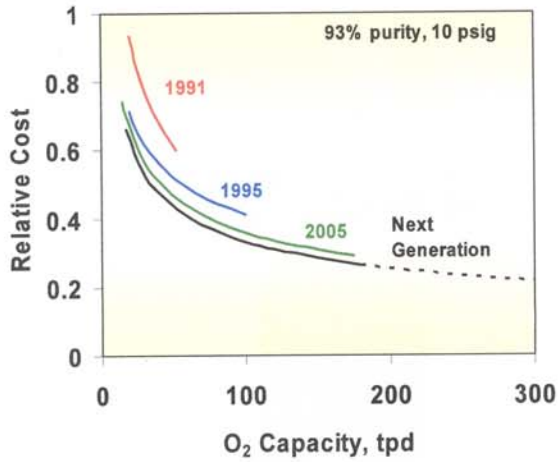
- Over 300 commercial oxy-fuel fired industrial furnaces in different industries
- Boiler Applications
  - Provided tech assistance to the first pilot scale oxy-FGR-coal boiler simulator tests by ANL-EERC in 1988
  - Advised on the pilot scale oxy-heavy oil fired industrial boiler (no FGR) project in Japan in 1993-1999
  - Joint techno-economic study with Alstom Power for oxy-fired refinery boilers with and without FGR in 2000
  - Commercialized the Oxygen Enhanced NOx Reduction Process for coal fired boilers in 2004 (30-50% NOx reduction in a125 MW utility boiler and two industrial boilers)



4

VPSA Oxygen

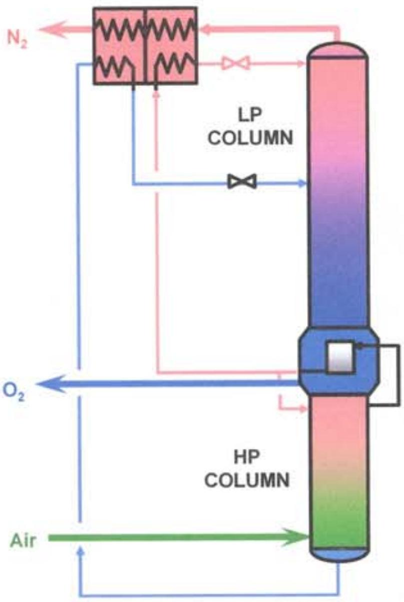
PRAXAIR

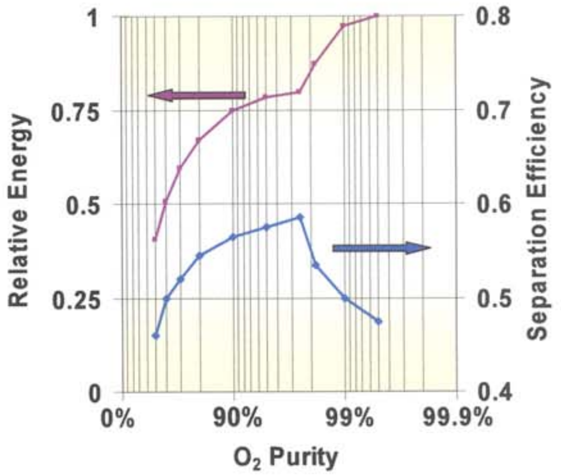


5

Conventional Oxygen Process

PRAXAIR





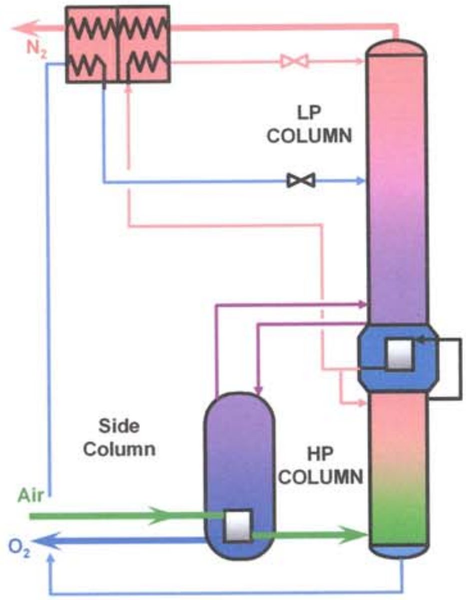
Note: Only separation energy in distillation shown here

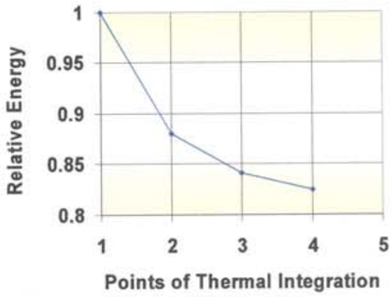
Peak efficiency at 97.5% purity

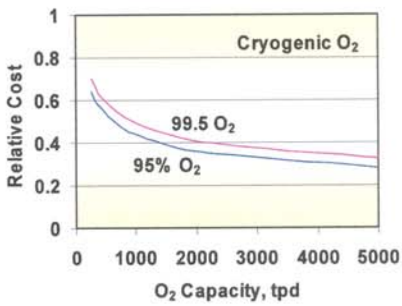
6

Low-Purity Oxygen Process

PRAXAIR







Increased thermal integration significantly reduces energy

7

CO_2 Purity Considerations for EOR

PRAXAIR

- **EOR Performance**
  - Minimum miscibility pressure (MMP), reservoir depth and oil's API gravity determines suitability of CO_2 for EOR
  - MMP decreases if the impurity has a greater critical temperature than CO_2
  - SO_2, H_2S, C_3+ decreases MMP
  - O_2, N_2, Ar, NO increases MMP
- **Pipeline Issues - Corrosion and Two Phase Flow**
  - With SO_2 present, H_2O must be reduced to very low levels (?)
  - O_2 with H_2O can accelerate cathodic reaction
  - High level of impurities could form second phase → Hammering
- **Reservoir Safety**
  - Oil operators prefer oxygen < 10 ppm
- **Minimum purity of 95% preferred**

CO_2 Purification designed to achieve <10 ppm O_2

8

CO_2 Purity for Sequestration

PRAXAIR

- CO_2 Sequestration/Storage Efficiency
  - Impact of impurities on integrity of injection well and geological formation?
  - Volume occupied by impurities
- Pipeline Network Considerations
  - Same corrosion issues as EOR
  - Interaction of impurities from different sources
    - Oxy-fuel: O_2, SO_2, NO
    - IGCC: H_2, CO, H_2S
    - Other sources - refineries, ethylene oxide, cement: ?
- CO_2 Compression
  - Power for compressing impurities vs. separating them

CO_2 Purification designed to achieve 96% CO_2

9

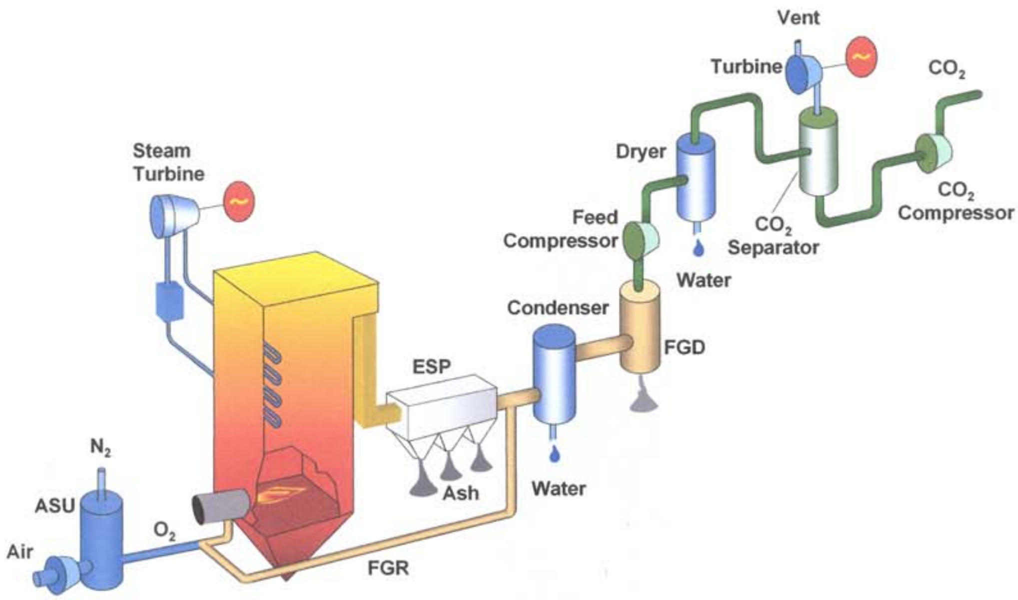
Baseline USC PC Boiler

PRAXAIR

Net power output	452 MW
Efficiency	44% (LHV)
Capital cost	$1200/kW
Coal	Illinois #6
CO_2 emitted	0.8 t(short tons)/MWh
Coal	$2/MMBtu (HHV)
COE	$43/MWh

10

Oxy-Fuel Schematics



11

Factors Affecting Power Consumption in CO_2 Processing

- Excess O_2 in Combustion
- Air Leak (% of wet flue gas before FGR)
- O_2 Purity
- CO_2 Purity

Excess O_2 %	Air Leak %	O_2 Purity %	CO_2 in Flue Gas %	Relative Power for CO_2 Processing/ton CO_2		
				Compressed as such	96% CO_2	99.9% CO_2
0	0	99.5	98.4	1.00		
15	0	99.5	94.0	1.05		
15	3	99.5	82.2	1.20	1.29	1.43
15	3	95.0	78.4	1.26	1.35	1.49

Air leak is a significant factor

12

Total Power Consumption in Oxy-Fuel Combustion

PRAXAIR

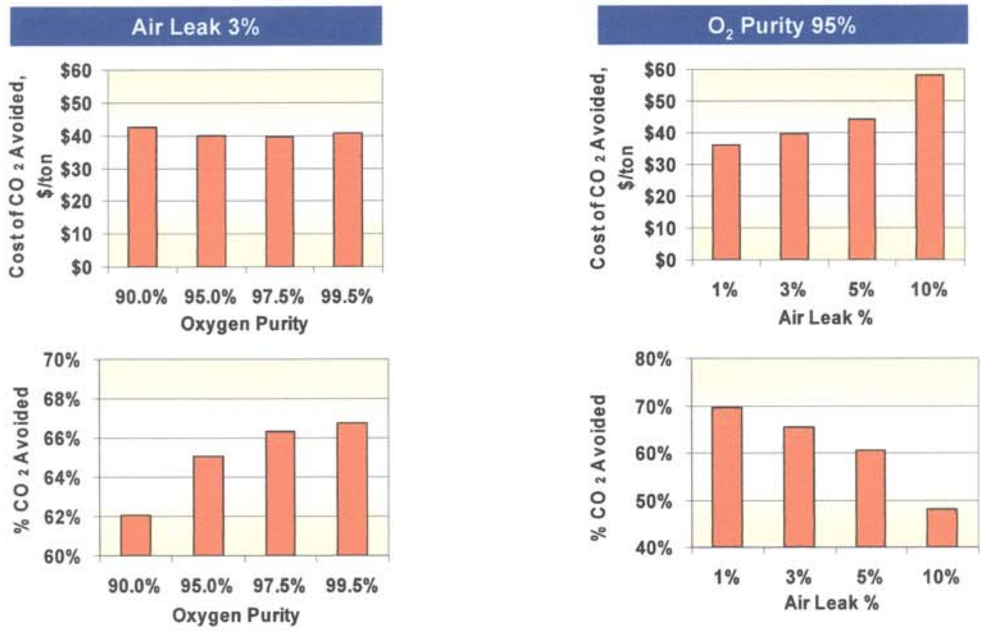
Excess O_2 %	Air Leak %	O_2 Purity %	CO_2 in Flue Gas %	Relative Power for ASU + CO_2 Processing/ton CO_2		
				Compressed as such	96% CO_2	99.9% CO_2
0	0	99.5	98.4	1.00		
15	0	99.5	94.0	1.02		
15	3	99.5	82.2	1.08	1.16	1.22
15	3	95.0	78.4	1.00	1.10	1.15

Power savings in 95% O_2 vs. 99.5% O_2 more than offsets extra power in CO_2 purification

13

Effect of O_2 Purity and Air Leak

PRAXAIR

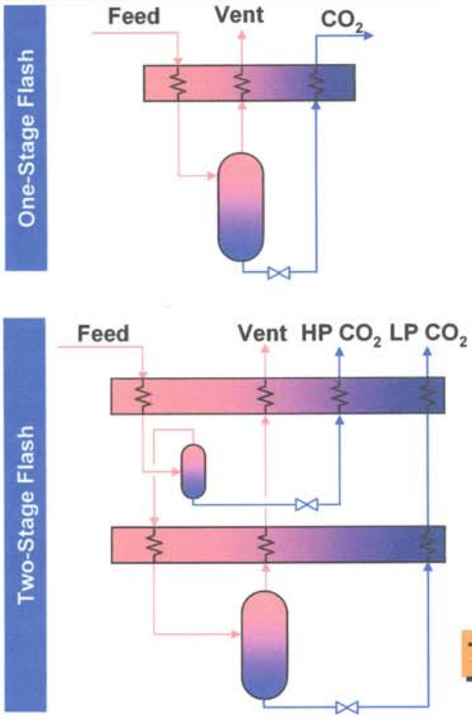


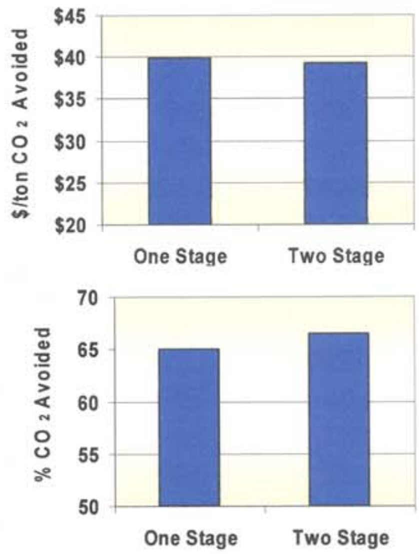
Minimizing air leak will benefit oxy-fuel combustion the most

14

One-Stage Flash vs. Two-Stage Flash

PRAXAIR



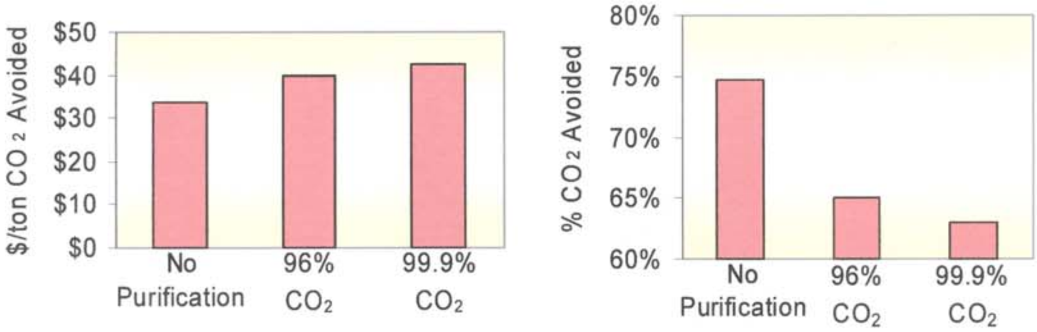


Two-stage flash provides slight advantage

15

Effect of CO_2 Purity Requirement

PRAXAIR



Need to define CO_2 purity requirement for sequestration

16

NOx and SOx

PRAXAIR

- Oxy-fuel combustion will reduce NOx generation
- NOx emissions will depend on CO_2 purification process
  - No purification - no emissions
  - 96% CO_2 - ~75% NO vented
  - 99.9% CO_2 - 100% NO vented
- If NOx control is desired, vent stream treated in SCR
- FGR will convert ~25% of SO_2 into SO_3, which will separate out during condensation of water
- SO_2 will remain with CO_2 after purification
- Drying CO_2 with SO_2 present is challenging
- Material of construction issues for processing SOx and NOx in cold box need to be investigated

17

Research Needs in CO_2 Processing

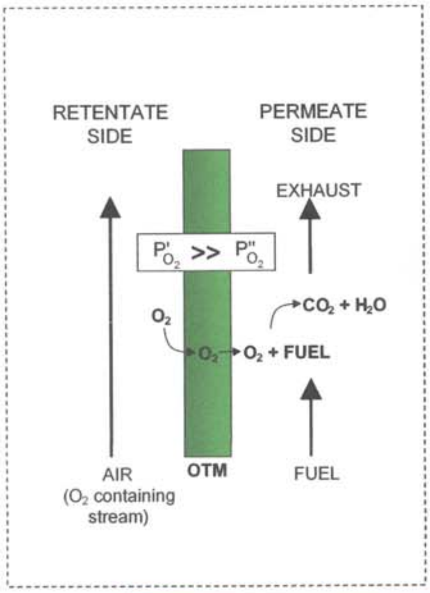
PRAXAIR

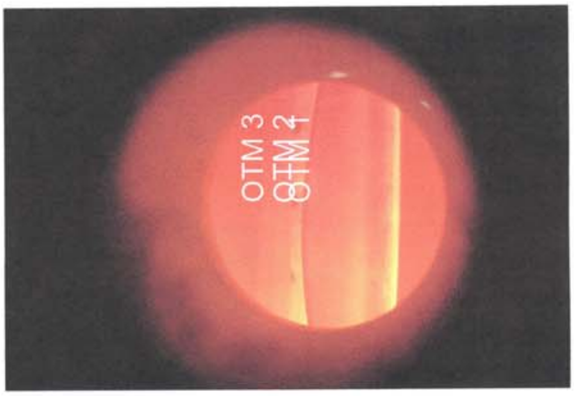
- Purity specifications for EOR and sequestration
  - Impact of impurities on pipeline materials
  - Impact of impurities on effectiveness of storage
  - Interaction with impurities from other capture sources
- Drying CO_2 containing SO_2
- VLE of high pressure CO_2 containing flue gas impurities

18

Praxair Advanced Boiler Concept

PRAXAIR





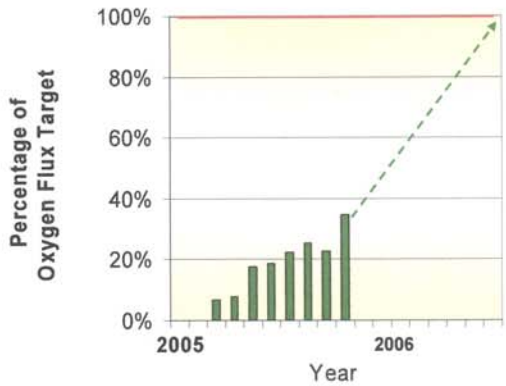
Oxy-fuel combustion without producing oxygen

19

Advanced Boiler Status

PRAXAIR

- Working with gaseous fuels on a bench-scale multi-tube reactor
- Developed reliable materials
  - Cumulative 10,000 hrs of failure-free operation
- Achieved 30% of commercial flux targets
  - Target flux by mid-2006



	Oxy-Coal Boiler 99.5% O_2	Adv. Coal Boiler 100% O_2
PowerGen Efficiency	34.5%	39.6%
Cost of CO_2 Avoided $/ton	40.8	30.0
% CO_2 Avoided	66.8	80.0

CO_2 Purity – 96%; Air Leak – 3%

20

Summary

- Praxair products/services for oxy-fuel combustion
  - Oxygen, CO_2 processing, burners, coatings for boilers and turbines
- Optimum oxygen purity 95 to 97.5%
- Minimizing air leak important for oxy-fuel combustion
- Need for CO_2 purity specifications
- Advanced boiler promising technology for future

21

Acknowledgements

- Sho Kobayashi, Dante Bonaquist, Neil Prosser, Ben Neu, Hank Howard, Bob Zawierucha, Bart VanHassel, Stefan Laux, all of Praxair
- Mark Holtz of Gulf Coast Carbon Center, U. of Texas at Austin

22

This page is intentionally left blank

Inaugural Workshop

International Oxy-Combustion Research Network

Vattenfall Europe Mining and Generation AG Head Office
Cottbus, Germany

29th and 30th November 2005

PRESENTATION - 11

Vattenfall Oxy-fuel Pilot Plant Study: Programme Overview

by:

Uwe Burchardt
Vattenfall Europe Generation and Mining AG, Germany

This page is intentionally left blank

VATTENFALL EUROPE

Oxyfuel Combustion Research Network IEA GHG Workshop

The Vattenfall Oxyfuel Pilot Plant

Cottbus, 30. November 2005
Uwe Burchhardt, Project Manager

VATTENFALL

VATTENFALL EUROPE

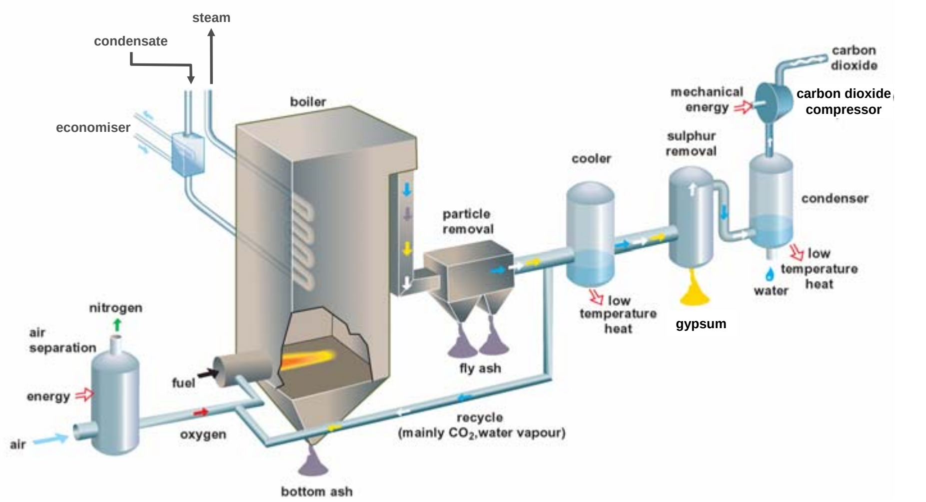
Steps toward the oxyfuel plant (Upscaling)

Development step	Scale-up Factor	Content	Year	Participant
Burning tests 10/55 kW (th.)		Basis tests to the Oxyfuel burning-behave	2004 2005	Uni Stuttgart (IVD), Chalmers University, TU Dresden, Vattenfall
Test rig 500 kW (th.)	1:50	Bases for the burning with recirculation	2006	CEBra, BTU Cottbus, Alstom, Vattenfall
Pilot plant 30 MW (th.)	1:60	Test of the complete technology chain	from 2008	Vattenfall
Demonstration plant approx. 600 MW (th.)	1:20	Realization with CO_2-transport and storage, proof of the economy	from 2015	
Commercial power station approx. 1000 MW (el.)	approx. 4-5	Costs for CO_2 capture, transport and storage < 20 € /t_{CO2}	from 2020	

30.11.2005 | Uwe Burchhardt | Vattenfall Europe Generation 2

VATTENFALL

Oxyfuel pilot plant process overview



Basic data

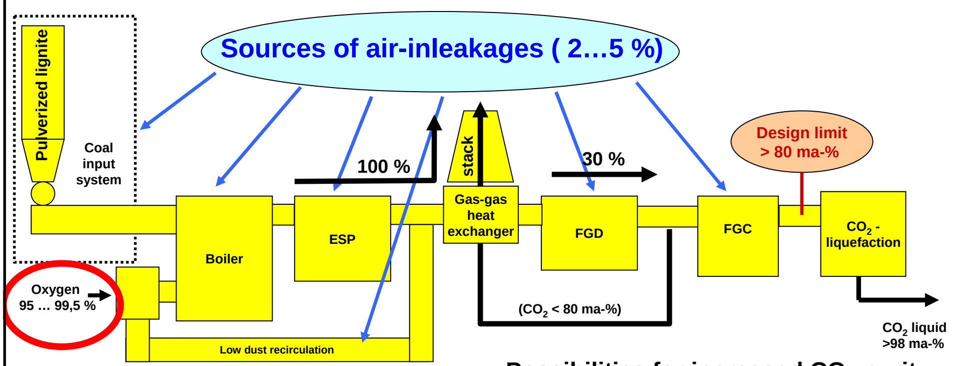
Boiler: dust fired	Combustion heat performance Steam production Steam parameter	30 MW_{th} 40 t/h 25 bar / 350 °C
Coal: pulverized lignite (Lausitz)	LHV Moisture Coal demand	21.000 kJ/kg 10,5 % 5,2 t/h
Media:	Oxygen (purity > 95%) Own consumption CO_2 (liquid)	8,5 t/h 6,5 MW 10 t/h
Other:	Required area Erecting time Investment	14.500 m² 22 month 37 Mio. €

Used fuel qualities

Fuel		Dry lignite dust		Bituminous coal		Light oil
		Design	Range	Design	Range	HEL
Granu-lation		0 – 1 mm		0-50 mm		
Distribution		60%< 0,1 mm 13%> 0,2 mm	3-18% >0,2mm	Max.15% bis 200 mm		
LHV		21,0 MJ/kg	20-22,5 MJ/kg	25,1 MJ/kg	23-26,8 MJ/kg	42,6 MJ/kg
Analyse	W	10,5 Mass%	8-12 M%	10,0 Mass%	7-21 M%	
	A	6,0 Mass%	4,5-7,5 M%	13,0 Mass%	5-17 M%	
	C	56,5 Mass%	54-60 M%	62,0 Mass%	56-71 M%	86,3 Mass%
	O_2	21,5 Mass%	20-22 M%	8,6 Mass%	??? M%	O = 0,4 M%
	H_2	4,0 Mass%	3,5-4,5 M%	4,2 Mass%	3,5-4,8 M%	H = 13 M%
	S	< 0,8 Mass%	0,4-1,2 M%	< 0,7 Mass%	0,3-1,0 M%	0,2 Mass%
	N	0,7 Mass%	0,6-1,1 M%	1,5 Mass%	1,0-2,0 M%	
	Cl		80-260 mg/kg			
	Fl		15-70 mg/kg			

Layout of flue gas way

Impact of Air- inleakages to CO2-purity

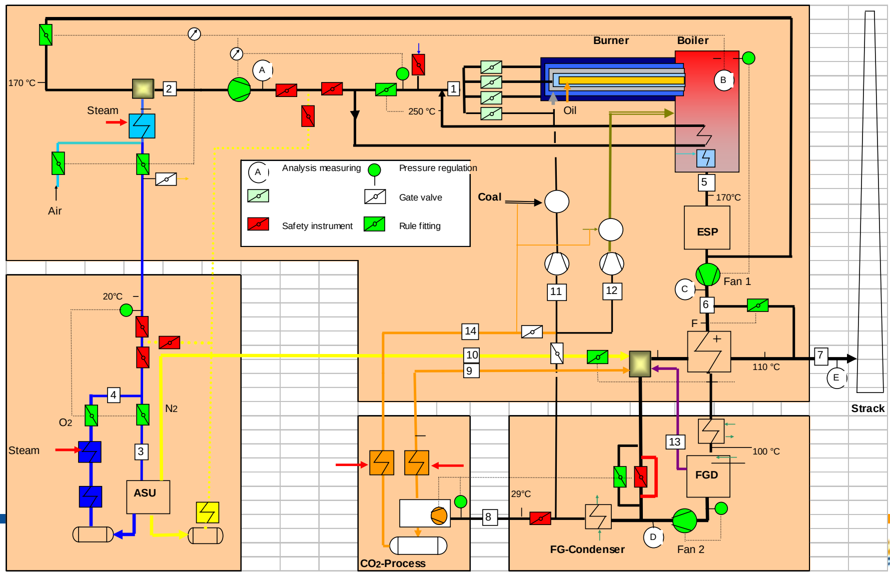


Consequence:
- liquefaction rate decreases rapidly
- high vent gas from CO_2-processing

Possibilities for increased CO_2-purity:
- optimized combustion
- eliminate leakages by sealing
- higher purity of Oxygen up to 99,5 %

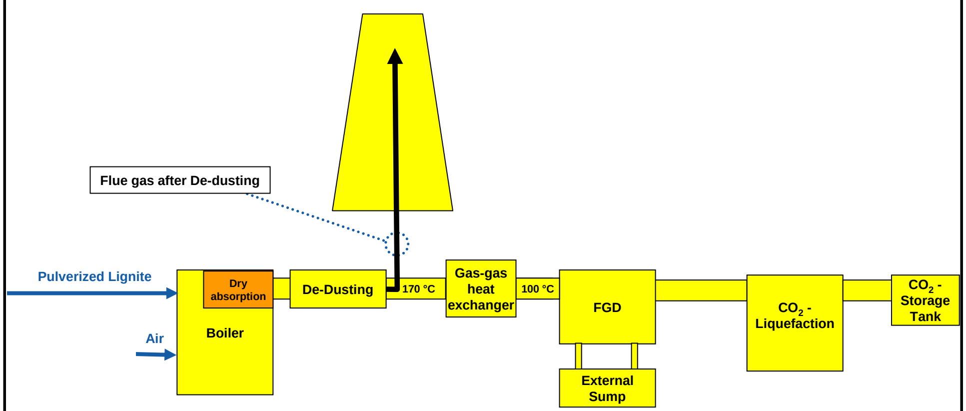
VATTENFALL EUROPE

Flow scheme of the pilot plant



VATTENFALL EUROPE

Operating status I: Air fired start up

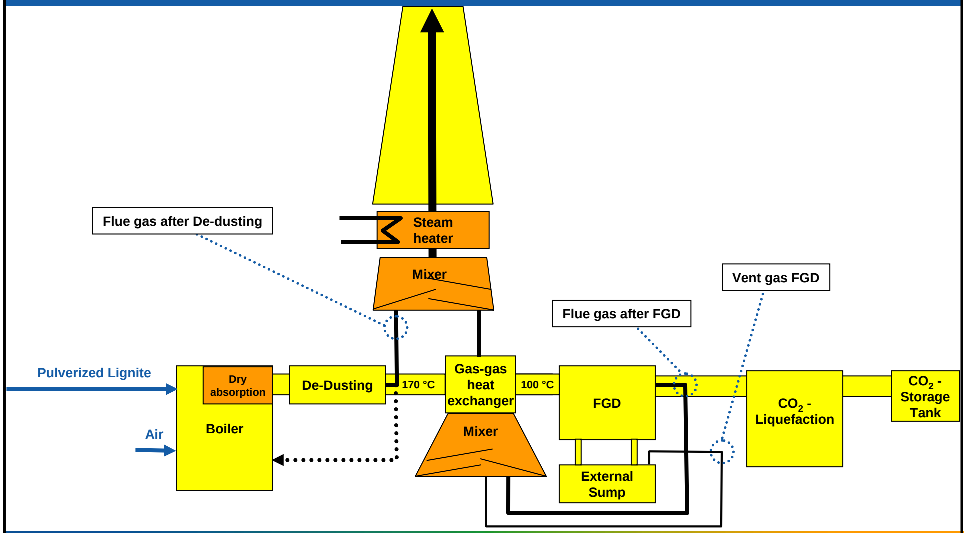


30.11.2005 | Uwe Burchhardt | Vattenfall Europe Generation 8

VATTENFALL

VATTENFALL EUROPE

Operating status II: Change load to Oxyfuel

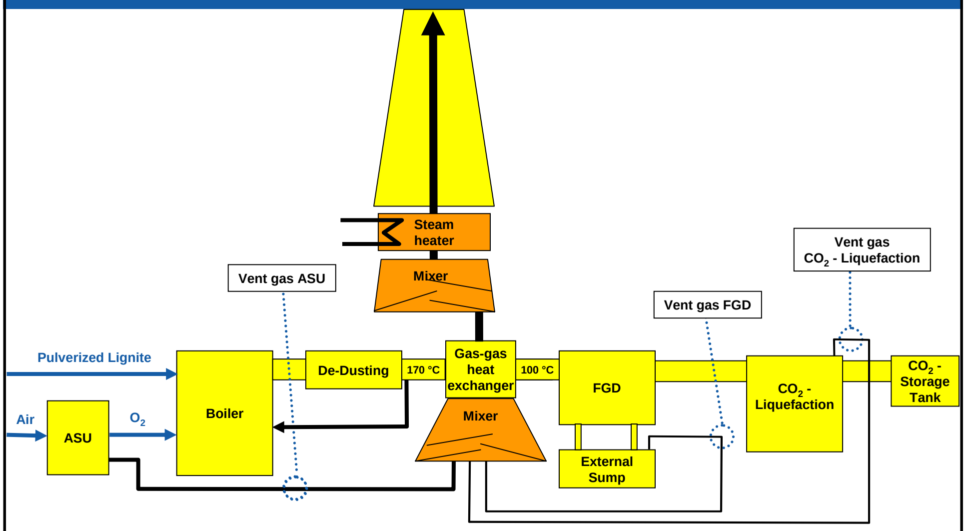


30.11.2005 | Uwe Burchhardt | Vattenfall Europe Generation 9

VATTENFALL

VATTENFALL EUROPE

Operating status III: Oxyfuel with CO_2 liquefaction

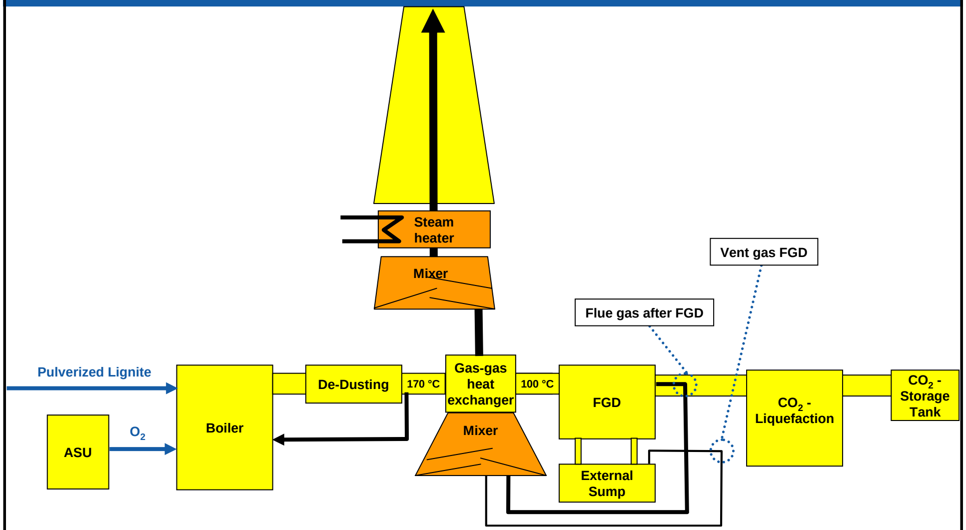


30.11.2005 | Uwe Burchhardt | Vattenfall Europe Generation 10

VATTENFALL

VATTENFALL EUROPE

Operating status VI: Worst case for gas dispersion

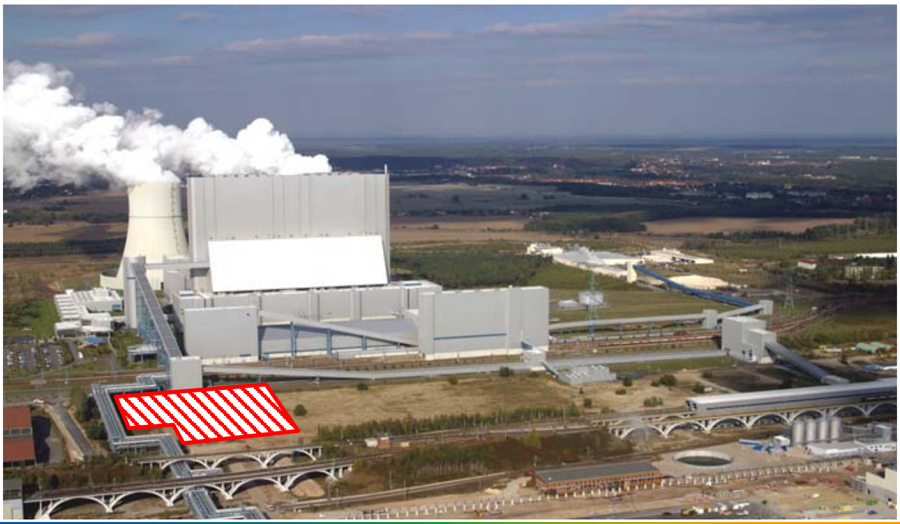


VATTENFALL EUROPE

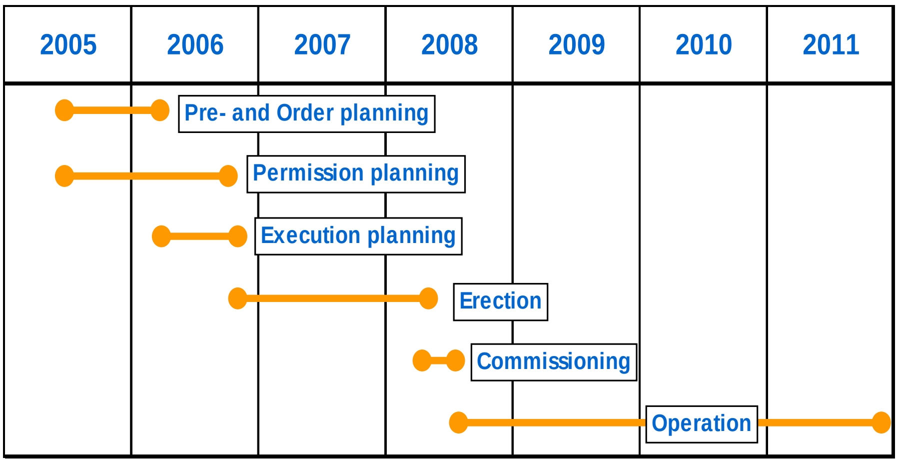
Aims of the "Oxyfuel Pilot Plant"

- Test of the complete technology chain (C-Input to CO_2- Purity)
- Proof of use of our local lignite
- The Boiler layout is considered to handle bituminous and lignite, with only a few modifications.
- Practical test of the interaction of all components
- Determination of the CO_2- capture rate and attainable CO_2 purity
- Testing of start up-and break downs, analysis of trouble cases
- Knowledge for officially demanded monitoring
- Experiences to the permission of a CO_2 free power station
- Formation of a platform for alternative coals and components
- Showing of potentials of the Oxyfuel technology for a commercial

Location of the pilot plant



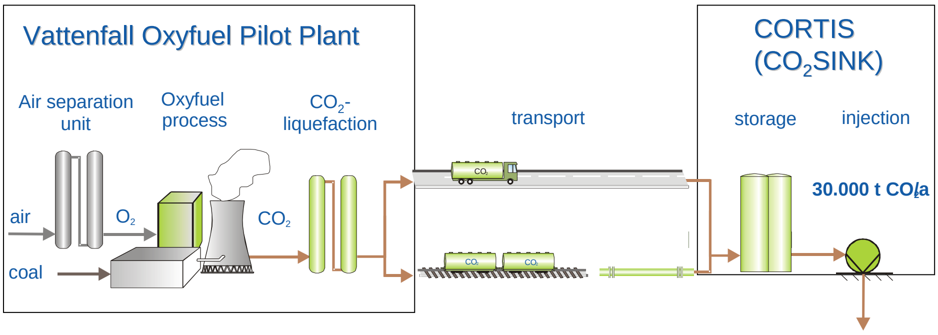
Time schedule



VATTENFALL EUROPE

Link to EU - project CO_2SINK

- The Vattenfall Oxyfuel Pilot Plant is a potential upstream supplier for CO_2SINK.
- Vattenfall is engaged in this issue to gain know-how in CO_2 - storage for potential commercial scale plants.



30.11.2005 | Uwe Burchhardt | Vattenfall Europe Generation 15

VATTENFALL

VATTENFALL EUROPE

Thank you for your attention

VATTENFALL

Inaugural Workshop

International Oxy-Combustion Research Network

Vattenfall Europe Mining and Generation AG Head Office
Cottbus, Germany

29th and 30th November 2005

PRESENTATION - 12

Australian Japanese Cooperation on OxyFuel Pilot Project for Plant Retrofit: The Callide-A Project

by:

Chris Spero
CSEnergy, Australia

This page is intentionally left blank

Overview of Australian-Japanese Callide A Oxy Fuel Demonstration Project

Presented by: Chris Spero

Project Manager Oxy-fuel F/S (CCSD)

Manager Engineering Technology (CS Energy)

IEA Greenhouse Gas R&D Program – Inaugural Workshop

Oxy-Fuel Combustion Research Network

Cottbus, Germany, 29-30 November 2005

Callide A Feasibility Study Contributors

NEDO		COAL21	Mark O'Neill/ Ross McKinnon
JCoal	Dr Takashi Kiga	CCSD	Frank van Schagen
IHI	Prof. Keiji Makino		Dr Lila Gurba
	Toshihiko Yamada		Dr Noel Simento
	Dr Toshiro Fujimori		Dr Louis Wibberley
	Barry Wairing		Doug Palfreyman
JPower	Nobuhiro Misawa	Xstrata Coal	Barry Isherwood
		Univ. Newcastle	Prof. Terry Wall
			Assoc. Prof. Rajender Gupta
			Sameer Khare
		ACARP	Mark Bennetts
			Jim Craigen
		CO2CRC	Dr Peter Cook
			Andy Rigg
			Dr Tobias Payenburg
		CS Energy	Dr Chris Spero
			Tony Andersen
		Stanwell Corp	Howard Morrison
		Tarong Energy	Burt Beasley

Presentation purpose & scope

Purpose:

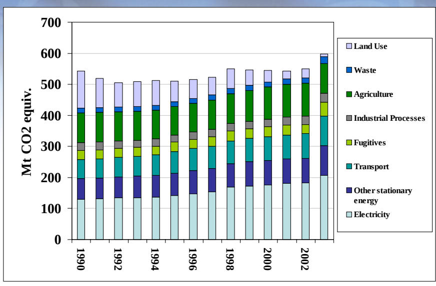
- To provide an update on the Australia-Japan oxy-fuel feasibility study and demonstration project implementation plan

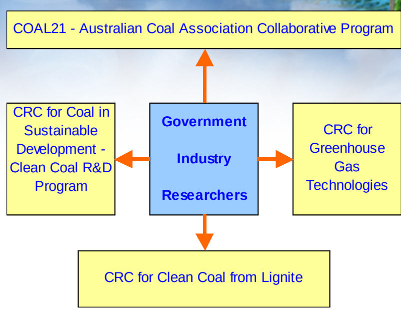
Scope of the presentation is:

- Australian scene, CS Energy & Callide A project background
- Technology comparison and oxy-fuel technology drivers in Australia
- Callide A project status report/results

cs energy CCSD

Australian scene





Commonwealth Government

White Paper: Securing Australia's Energy Future (June 2004)

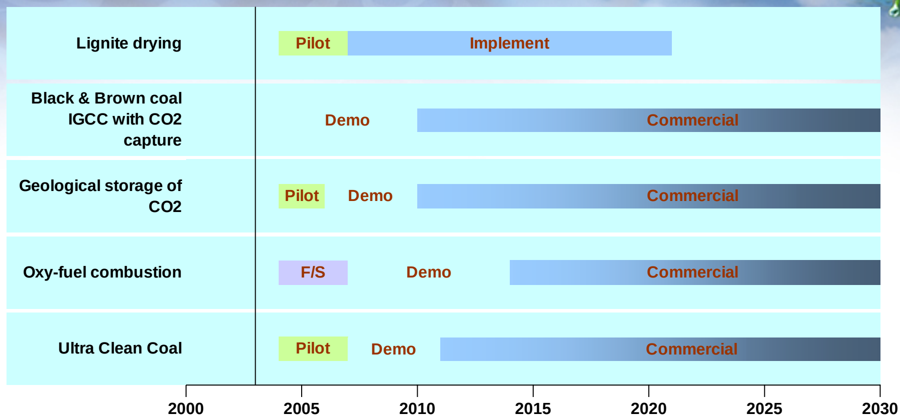
$500 million Low Emission Technology Fund
Clean coal demonstrations
Renewable demonstrations

Asia-Pacific clean development and climate partnership (APP)

- Inaugural meeting scheduled 10 – 13 Jan. 2006 (Sydney)
- Development & deployment of clean fossil technologies, enhancing capacity and developing markets, and growing the research and education base

cs energy CCSD

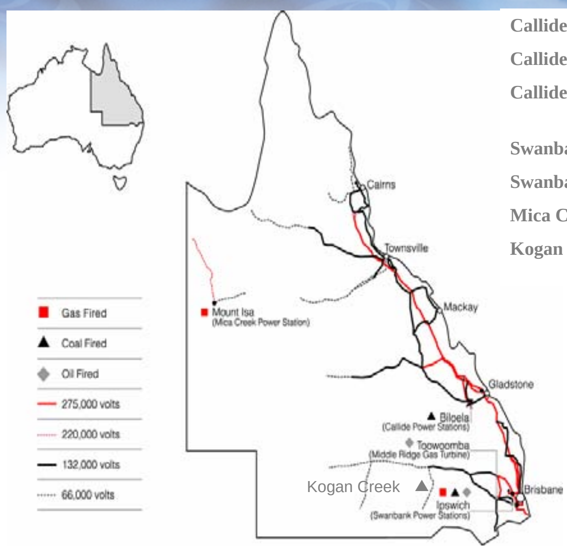
COAL21 Roadmap



F/S - Feasibility Study

cs energy CCSD

CS Energy



Callide A: 4 x 30 MWe (PF)

Callide B: 2 x 350 MWe (PF)

Callide C: 2 x 460 MW (PF)
Joint Venture (50%)

Swanbank B: 4 x 120 MW (PF)

Swanbank E: 1 x 385 MW (CCGT)

Mica Creek: 327 MW (Gas & CCGT)

Kogan Creek: 1 x 750 MWe (PF)
(under construction)

cs energy CCSD

CS Energy Production Statistics 2004/05

Total capacity	**2470 MW**
	(+ 750 MW under construction at Kogan Creek)
Electricity sent-out	**12.490 TWh**
Electricity from coal	**75.7 %**
Electricity from gas	**24.0 %**
Electricity from renewables	**0.3 %**

cs energy CCSD

Comparison of technologies

Case	Pnet	Pgross	NTE	Coal	O2	N2	Processed Gas	CO2	SOx	NOx	Part.	Ash
	MWe	MWe	%, HHV	kg/s				kg/MWh SO				
Air-fired PF	500	524	41	49	110	350	500	780	3.0	1.9	0.10	75
Air-fired PF + Capture	500	633	34	59	130	415	610	100	3.7	2.3	< 0.01	90
Oxy-PF + Capture	500	633	34	59	130	3	180	100	0.02	0.9	< 0.01	90
IGCC + Capture	500	588	35.7	56	40	1	85	95	0.01	0.1	< 0.01	85

Assumptions:

Coal gross calorific value = 25 MJ/kg

Ash = 21 %, ar

Super-critical power plant, net thermal efficiency = 41%, HHV

Excess combustion O2 = 3.2 mass %, dry

CO2 recovery from oxy-firing = 90%

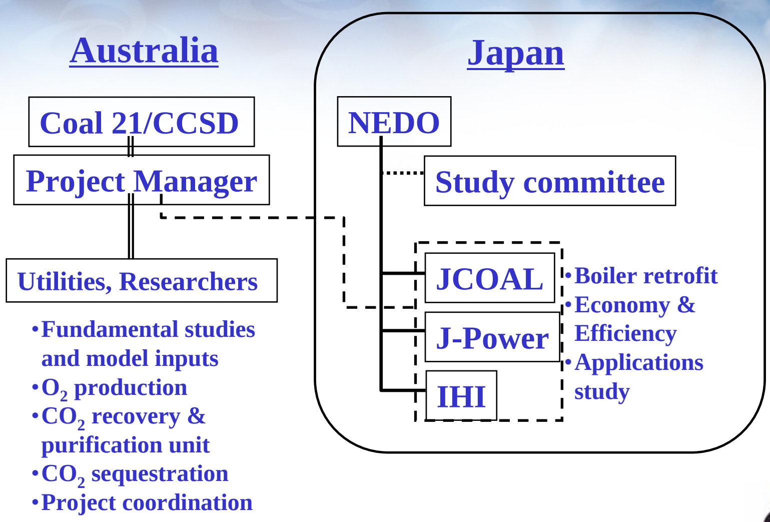
cs energy CCSD

Project history

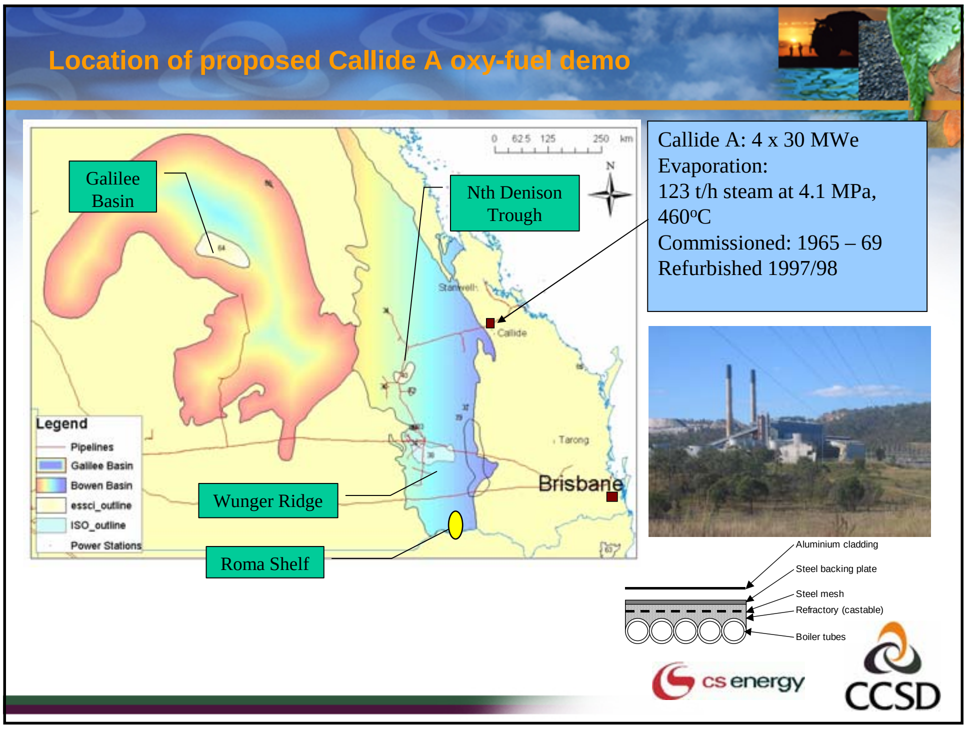
Period	Activity
1992 - 2000	NEDO (Japan) with IHI funded the construction of a 150 kg/h pilot facility. A series of tests were conducted and CO2 was liquefied from a flue gas stream. Process design and assessment made of a 1000 MWe super-critical boiler.
Nov. 2002	At the 1st CCSD Annual Conf. Prof. Keiji Makino presented on the Japan Technology Road Map – which included oxy-firing.
Apr. 2003	Meeting at Newcastle (Wall, Beasley, Wibberley, Makino, Waining & Spero) to discuss R&D in oxy-fuel in Australia. CCSD Project 3.4 was initiated.
Nov. 2003	Submission prepared on an oxy-fuel feasibility study for COAL21 National Plan of Action.
Mar. 2004	COAL21 National Plan of Action launched.
Apr. 2004	CCSD/COAL21 Oxy-fuel Working Group formed, and CCSD Project 3.5 was developed.
Sep. 2004	MOU signed to formalize oxy-fuel feasibility study.

cs energy CCSD

Project structure



cs energy CCSD


Location of proposed Callide A oxy-fuel demo
Galilee Basin
Nth Denison Trough
Wunger Ridge
Roma Shelf
Stanwell
Callide
Tarong
Brisbane
Legend
Pipelines
Galilee Basin
Bowen Basin
essci_outline
ISO_outline
Power Stations
Callide A: 4 x 30 MWe
Evaporation:
123 t/h steam at 4.1 MPa, 460ºC
Commissioned: 1965 – 69
Refurbished 1997/98
Aluminium cladding
Steel backing plate
Steel mesh
Refractory (castable)
Boiler tubes
cs energy
CCSD


Queensland Petroleum Fields-Denison Trough
Turkey Creek
Arcturus
Rolleston
30.7% CO2
23.6% CO2
10.8% CO2
Commercial gas accumulation
Non-commercial gas accumulation
Courtesy: CO2CRC
cs energy
CCSD

Demonstration plant feasibility study

- Primary objective
  - To assess the technical and economic merits of oxy-fuel combustion
- Deliverables
  - Feasibility study report including results of applications study (based on 1000 MW plant simulation)
  - Callide A 30 MWe demonstration plant – Reference Design
- Long-term Goal
  - To facilitate the development of alternative near zero emissions technology for electricity generation, that can be underpinned commercially

cs energy CCSD

Project tasks

Feasibility study (under CCSD R&D Program)

- Initial process design
- Assessment of primary design factors:
  - Coal reactivity
  - Radiative and convective heat transfer
  - Ash characteristics
  - Emissions
- Process optimisation
- Preliminary design, layout and costing of O2 plant and product recovery train
- Detailed design, layout and costing of the Callide A retrofit
- CO2 preliminary storage site assessments
- Large-scale applications study

Engineering design & financial close

- Reference design/EPC specifications/EIS/Risk review/final costing
- Contracts for construction
- Incorporated Joint Venture Agreement
- Agreements for funding, O&M, and services

cs energy CCSD

Test & evaluation

– Laboratory measurements and theoretical calculations combustion behaviour oxy-firing (O2/CO2) with air firing (O2/N2)
  - Volatile matter yield and char reactivity
  - Melting characteristics of the coal ash
  - Boiler heat transfer characteristics/design parameters
    – Emissivity of particles and gas
    – Adiabatic flame temperature vs O2 concentration and flue gas recirculation rates
    – Heat absorbed by furnace
– Purpose of the measurements are:
  - Data input to the IHI boiler model
  - Optimisation of oxy-firing conditions and matching of boiler heat transfer characteristics between oxy- and air-firing

cs energy CCSD

Test coals

Coal		Reference Coal 1	Design Coal 2	Coal 3	Coal 4	Coal 5
		Drayton	Callide	Callide – Low CV	Acland	Rolleston Premium Export
Total Moisture	%, ar	9	14	12.8	8	14.9
Ash	%, ar	12.6	21.5	30.7	21.7	6.4
Volatile matter	%, ar	32.1	22.0	20.3	35.7	29.2
	%, daf	40.9	34.1	35.92	50.8	37.1
Gross Calorific Value	MJ/kg, ar	26.88	19.1	15.85	24.24	24.43
	MJ/kg, daf	34.29	29.61	28.05	34.48	31.04
Carbon	%, daf	83.3	77.8	74.4	80.8	78.4
Hydrogen	%, daf	5.78	4.4	4.46	6.96	4.96
Nitrogen	%, daf	1.79	1.14	1.13	1.14	2.10
Sulfur	%, daf	1.13	0.27	0.3	0.62	0.76
Oxygen	%, daf	8.00	16.39	19.71	10.48	13.78
Ash Fusibility - Reducing						
Deformation	°C	1280	1400	>1600	1510	1140
Sphere	°C	1300	1470	>1600	1600	1220
Hemisphere	°C	1320	1480	>1600	>1600	1240
Flow	°C	1380	1500	>1600	>1600	1260
Silica/Alumina ratio		1.81	2.11	1.74	4.02	2.43
Fe2O3 in Ash	%		12.7	3.3	0.5	14.9

Rolleston coal mine

cs energy CCSD

Coal reactivity studies

Drop tube & TGA Experiments

- O2/N2 vs O2/CO2
- High Temp VM
- Char reactivity (pre-exponential factor)
- Pyrolysis rates

Coal	Callide		Acland	Rolleston
	Design	Low CV		
VM (%, ad)	25.6	24.5	40.5	33.8
V^*_{N2} (%, daf)	36.7	30.9	52.4	53.5
Q factor	1.43	1.26	1.29	1.58
V^*_{CO2} (%, daf)	43.3	32.2	55.3	66.2
Q factor	1.69	1.32	1.36	1.96

PF: 63 – 90 um

Modelling

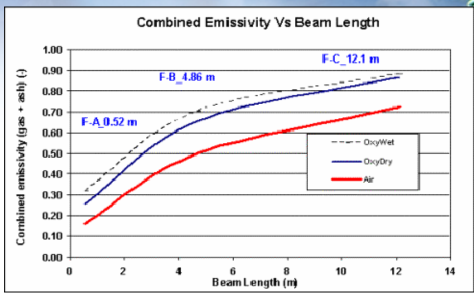
- IHI CFD Model for Callide A to evaluate effect of O2 on heat transfer
- Fluent model also being developed
- 1st order kinetics to be verified

cs energy CCSD

Emissivity calculations

Furnace – Radiative heat transfer modelling

- Emissivity of gas and particles
- Emissivity vs beam length
- Emissivity vs temperature
- Comparison of air combustion vs wet RFG vs dry RFG



Callide coal, gas at 1670 K

Exponential wide band (spectral) model used for real gases

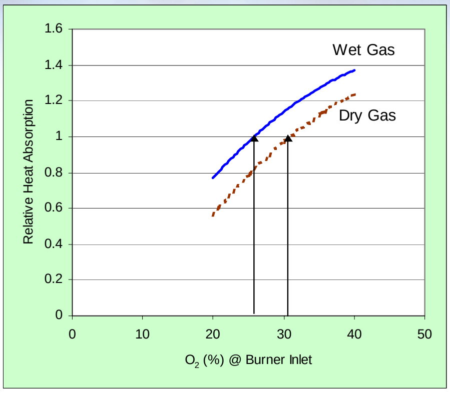
Emissivity of gas + ash particles

Simulation of real gases based on 3 or 4 gray gas model

Application of single zone model to predict heat transfer effects

cs energy CCSD

Callide A - Furnace heat absorption



$$RHA = \frac{Q_{ox} / H_{f,ox}}{Q_a / H_{f,a}}$$

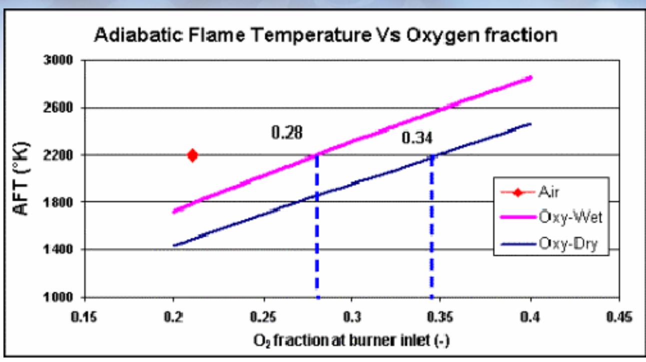
RHA = Relative Heat Absorption

Q_{ox} and Q_a = Heat absorbed under oxy-firing and air-firing conditions, respectively (MW)

$H_{f,ox}$ and $H_{f,a}$ = Heat input under oxy-firing and air-firing conditions, respectively (MW)

cs energy CCSD

Adiabatic flame temperature comparison



Callide coal

Oxy-firing:

•Increases emissivity

•Increases heat absorption

cs energy CCSD

Convective heat transfer

- Convective heat transfer model looks at comparative heat absorption
- Effected by volume of gas, composition and ptroperties (including T)
- Lower heat transfer is due to gas volume reduction and changes to gas properties

Gas		Air case	Oxy (Dry)	Oxy (wet)
Tc, in	K	1432	1365	1348
u	m/s	9.8	5	7.5
Tc, out	K	700	547	653
h	W/m^2K	46.4	39.4	48.9
Delta h			-15	5.4

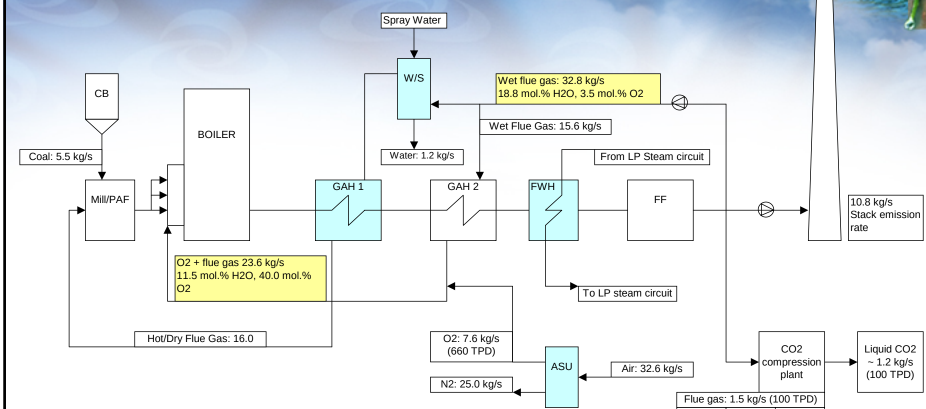
cs energy CCSD

O2 production & CO2 capture

- The purity of O2 from the Air Separation Unit and the level of air ingress into the boiler will impact of the CO2 recovery system in terms of:
  - Power consumption
  - CO2 liquefaction temperature
  - CO2 capture rate
- Modeling work has been done for both a large scale (450 MWe) and the Callide A plant, to assess the effects referred to above.
- Budget proposals, including preliminary process flowsheets, layouts, performance data and costs, have been obtained from two major plant suppliers.
- A budget proposal has been obtained for a 100 TPD CO2 recovery plant for the Callide A demonstration project.

cs energy CCSD

Callide A – Oxy-firing flow sheet



	Mol. %	Mass%
H2O	18.8	9.3
O2	3.5	3.1
N2	15.0	11.5
CO2	62.7	75.9
SO2	0.2	0.2

Coal	**400 TPD**
Oxygen	**600 TPD**
CO2 product recovery	**100 TPD**

cs energy CCSD

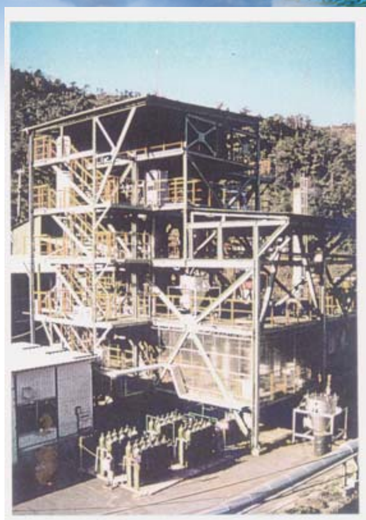
Pilot-scale testing at Aioi (Japan)

Test facility:
- Capacity 1.2 MWt (~ 150 kg coal/h)
- Furnace size – 1.3m dia x 7.5 m

Objectives:
- Compare air- vs oxy-firing combustion and emissions
- Additional validation of Callide A boiler model
- Investor confidence
- Ash samples for other CCSD Projects

Status:
- Callide & Acland coals tested in Sep. 05
- Rolleston coal to be tested in Dec. 05

Measurements:
- Burnout and temperature profiles
- Ash deposition tares
- Emissions including Hg
- Turn-down effects
- Fly ash for characterization



全景 General View

cs energy CCSD

Oxy-fuel pilot tests (Sep. 05)

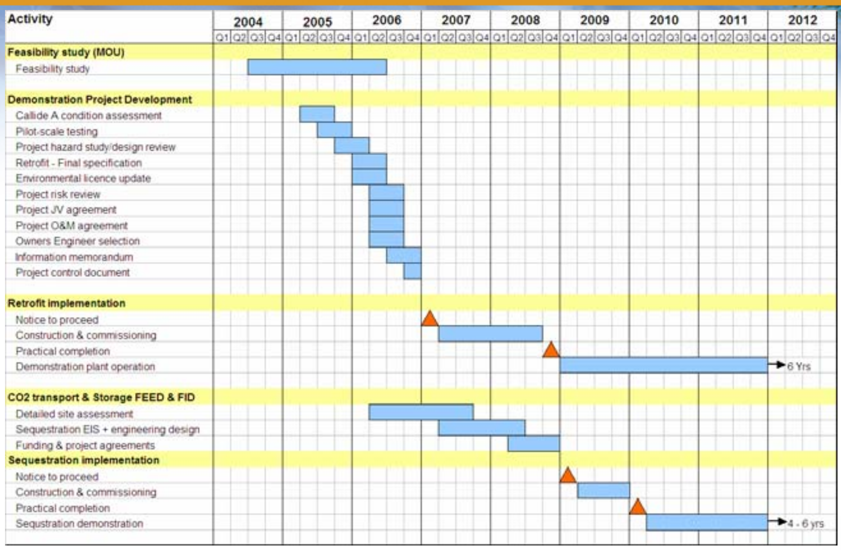
cs energy CCSD

Demonstration plant objectives

- Large scale test facility for integrated O2 production, oxy-firing and CO2 capture & liquefaction
  - As a design assessment facility – applicable to both retrofit and new oxy-fuel projects
    - Burner assessment
    - Effect of process variables (such as dilution with air) on combustion performance, downstream effect on CO2 compression plant, and overall environmental performance.
    - Testing of heat exchanger materials for oxy-firing applications.
    - Assess system control (firing rate, O2 injection rate, Flue gas recirculation rate
  - Assess and predict oxy-fuel costs (CAPEX, OPEX)
  - Assess O&M issues and costs
  - Test facility for other coals
- Source of CO2 for geological storage demonstration

cs energy CCSD

Development program



cs energy CCSD

Project value proposition

– Oxy-fuel technology is a key enabling technology for CO2 capture and sequestration and substantial reductions in other emissions
– Key knowledge gaps and issues need to be addressed at full-scale, viz.,
  - Coal ignition, stability, detection and turndown
  - Radiative and convective heat transfer
  - Final gas temperature, dew point, material corrosion
  - Optimization of Product Recovery Train
– The Callide A demonstration project, at a modest cost, could provide a platform for commercialization of oxy-fuel technology and set a new technology benchmark
– Plus substantial IP benefits for future large scale plant design and implementation
– Next steps are to finalize feasibility study, IJV agreement, project business plan and demonstration fund application

cs energy CCSD

Callide A – From the west

Callide A – East side

Proposed area for
ASU and CO_2 train

This page is intentionally left blank

APPENDIX 3

Oxy-Combustion Issue Paper

1st International Oxy-Combustion Workshop
Cottbus, Germany
29th – 30th November 2005

1. Background

This issue paper was prepared by IEA Greenhouse Gas R&D Programme in co-operation with Prof. Terry Wall and Prof. Keiji Makino.

This paper was distributed among the participants of the workshop with an aim to provide a brief overview of the various issues involving in development of oxy-combustion technology for power generation to be discussed during the workshop. These questions was used as the basis for discussion by Dr. Sho Kobayashi who was the moderator during the discussion session.

Additional comments and feedback were collected after the workshop and the results were summarised below.

This is an informal survey initiated by IEA Greenhouse Gas R&D Programme to help identify other issues that were not discussed during the workshop. In the future, the discussion and other points arise from this informal survey will be reviewed and discussed during future workshop.

2. Summary of Results

The informal survey received 14 replies from the participants of the workshop.

Among the 30 questions presented in the issue paper, the questions listed obtained greater than 4 votes from the respondents. Table A3-1 shows the list of questions with their corresponding votes.

Question	Votes
30. What is the purity of CO_2 required for transport and further usage/storage? 30.1. Is there a CO2 purity required for compression? Is a binary equilibrium approximation suitable for this estimation? 30.2. To what extent it is necessary to remove non-condensable gas from the flue gas stream? 30.3. To what level dehydration of the flue gas is necessary to prevent any corrosion within the transport line? 30.4. To what extent should SO_2 / NOx and other pollutant to be separated from the final flue gas stream?	**11**

1. For a boiler retrofit, what is the optimum recycled flue gas ratio where heat transfer profile could be similar to the air-fired system, and will this be dependent on the type of boiler and its configuration? – Clarification should be made from the different values reported in the literature. Different parameters that have an affect on the optimum amount of flue gas recycled should be elucidated.	**10**
8. What are the data available in characterisation and performance of different type of coal under the firing condition of an $O_2/CO_2/H_2O$ environment? 8.1. Where are we in the understanding of the devolatilisaton and char burnout properties of the coal under oxy-firing environment? 8.2. Where are we in the understanding of coal ignition (related to coal devolatilisation) and level of unburned carbon in ash (related to char burnout)? 8.3. How could we consolidate available experimental data to develop models for devolatilisation and char burnout kinetics under oxy-firing conditions? What further experiments are required to compliment or supplement the available data? 8.4. Will flame detection techniques differ for oxyfuel firing?	**10**
10. It has been reported that NOx and SO_2 emission tend to reduce during oxy-firing conditions; unfortunately, mechanisms behind these reduction has yet to be understood. What else to be done to reinforce the studies done during the 1990's funded under NEDO project to achieve a good understanding in aid to model development?	**10**
2. For new boiler development, what are the experimental data available to enable the development of CFD models that will aid in the determination of the optimum flue gas recycle ratio and the design of appropriate boiler size and configuration?	**9**
27. What is the dynamic matching between oxygen production,. boiler operation and CO_2 processing? What is the process bottle neck when operating oxyfiring unit under higher load change?	**8**
9. What are the different flame properties in terms of varying flue recycle ratio? 9.1. Where are we in the understanding gas phase chemistry and kinetics under a combustion regime of $O_2/CO_2/H_2O$ atmosphere? 9.2. What is the optimum level of excess oxygen necessary for complete burnout of CO and char? 9.3. For boiler retrofit, it is established that volume is reduced during oxy-fired conditions with optimum flue recycle ratio – similar heat transfer profile to air fired system; do we have good understanding on issues relevant to the aerodynamics mixing? combustion rate?	**8**

17.	What is the behaviour of ash under $O_2/CO_2/H_2O$ atmosphere in terms of slagging and fouling propensity? Will the ash deposition characteristics differ to the air-fired system?	**8**
6.	What are the different issues to be considered in terms of the level of treatment necessary for the recycled flue gas?	**6**
19.	What are the effect of $O_2/CO_2/H_2O$ environment to the metal and refractory materials and its propensity of high temperature corrosion?	**6**
11.	Some literature has also reported increased in SO_3 and retention of sulphur in the ash. What level of understanding do we have on this issue?	**5**
16.	Given our understanding regarding corrosion and SO_2/SO_3, will the oxy-fuel firing techniques be limited to low sulphur coal?	**5**
21.	What operational factors must be established in demonstration, including O_2 supply for load following?	**4**
7.	What correlations could be established between amount of flue gas recycled and the different heat transfer properties (ie. radiative heat flux to the wall, heat transfer coefficient and many others)?	**4**
12.	Improvement of sulphur capture in FGD operation has been reported when firing coal under oxy-firing conditions. To what extent can we verify these results?	**4**

Development of Oxy-Coal Combustion for Power Generation Industry
Issue Paper

IEA Greenhouse Gas R&D Programme

****

OVERVIEW

This document provides a series of questions that are relevant to the development of the oxy-coal combustion as an option for carbon capture technology in the power generation industry.

The inaugural workshop of the Oxy-Fuel Combustion Network aims to address developmental issues through presentation of data and discussion of results. **One of the primary objectives of this workshop is to list down the critical issues which limit oxyfuel applications and development.**

Submissions from participants regarding these issues will be welcome. Please feel free to also add any other issues required for the discussion. These will be circulated to participants of the workshop.

****

AGENDA

The main objective of the International Oxy-Fuel Combustion Network is to establish a forum where people could open up discussion on several issues important to the successful development and demonstration of this technology.

The ultimate goal is to provide an avenue that will create environment where information could be shared in a manner that could be mutually beneficial to participants.

It is envisioned that the inaugural workshop could be an opportunities where co-operation among interested parties could be established. We aim to achieve this by bringing together engineers, researchers and scientists who are working on this area to initiate the discussion.

For the inaugural workshop, the following agenda were put on the table for an open discussion and these could be subdivided in the following headings:

- Burner and Boiler Development
- Plant Operation and Safety Issues
- O_2 Production and CO_2 Processing and Compression
- Development of Large Scale Pilot Plant and Demonstration Studies

For this document, a series of questions were presented under each sub-group to stimulate discussion during the workshop. The discussion will not, however, be limited to these questions as participants will be free to raise other issues.

Many potential issues are listed here, but the Network meeting should identify the **critical issues limiting oxyfuel development**, as well as considering those desirable. In other words, what are the real priority areas?

I. KEY ISSUES INVOLVING BURNER AND BOILER DEVELOPMENT

It could be established that issues relevant to burners and boiler performance optimisation when firing under $O_2/CO_2/H_2O$ environment will require further experimental work and CFD modelling studies. Consideration should be stressed in the understanding of the effect of coal properties and the amount of flue gas recycled to the different flame properties, near-burner aerodynamics, burner-burner / burner-"overfire air" interaction and boiler configuration.

Most notable difference between oxy-fired and air-fired system is the variation of the heat transfer profile due to the different properties of CO_2 and H_2O as compared to N_2. This could clearly affect the thermal performance of the boiler, and there may be local regions of excessive heat transfer in some cases.

Further studies are also necessary in the development where internal flue gas recycle could be used to reduce the amount of external flue gas recycle required. Several combustion techniques have been applied in controlling flame temperature in different oxy-fuel burners used in other industries. This could help in the reduction of boiler size, reduction in the requirement of ID fan for flue gas recycle and as a result an increase in the overall efficiency.

Issues Regarding Recycled Flue Gas

It is expected that firing of any fuel with oxygen tends to increase temperature and reduce volume of the combustion products. To moderate the flame temperature, a part of the flue gas is recycled. This determines the O_2 level through the burner. However, it is well established that there is an upper limit on the amount of flue gas that can be recycled to maintain a stable flame.

On issue related to effect of flue gas recycle, a series of questions where presented below for further discussion.

31. For a boiler retrofit, what is the optimum recycled flue gas ratio where heat transfer profile could be similar to the air-fired system, and will this be dependent on the type of boiler and its configuration? – Clarification should be made from the different values reported in the literature. Different parameters that have an affect on the optimum amount of flue gas recycled should be elucidated.

32. For new boiler development, what are the experimental data available to enable the development of CFD models that will aid in the determination of the optimum flue gas recycle ratio and the design of appropriate boiler size and configuration?

33. What recycle ratio that will prevent any flame blow out or burner over heating?

34. What are the different flame shapes / heat transfer profile at different level of flue gas recycle ratio and during turn-down operation?

35. What are the different issues to be considered regarding the use of "Wet Recycle" or "Dry Recycle"?

36. What are the different issues to be considered in terms of the level of treatment necessary for the recycled flue gas?

37. What correlations could be established between amount of flue gas recycled and the different heat transfer properties (ie. radiative heat flux to the wall, heat transfer coefficient and many others)?

Flame Properties

38. What are the data available in characterisation and performance of different type of coal under the firing condition of an $O_2/CO_2/H_2O$ environment?

    38.1. Where are we in the understanding of the devolatilisaton and char burnout properties of the coal under oxy-firing environment?

    38.2. Where are we in the understanding of coal ignition (related to coal devolatilisation) and level of unburned carbon in ash (related to char burnout)?

    38.3. How could we consolidate available experimental data to develop models for devolatilisation and char burnout kinetics under oxy-firing conditions? What further experiments are required to compliment or supplement the available data?

    38.4. Will flame detection techniques differ for oxyfuel firing?

39. What are the different flame properties in terms of varying flue recycle ratio?

    39.1. Where are we in the understanding gas phase chemistry and kinetics under a combustion regime of $O_2/CO_2/H_2O$ atmosphere?

    39.2. What is the optimum level of excess oxygen necessary for complete burnout of CO and char?

    39.3. For boiler retrofit, it is established that volume is reduced during oxy-fired conditions with optimum flue recycle ratio – similar heat transfer profile to air fired system; do we have good understanding on issues relevant to the aerodynamics mixing? combustion rate?

Pollutant Formation and Reduction

40. It has been reported that NOx and SO_2 emission tend to reduce during oxy-firing conditions; unfortunately, mechanisms behind these reduction has yet to be understood. What else to be done to reinforce the studies done during the 1990's funded under NEDO project to achieve a good understanding in aid to model development?

41. Some literature has also reported increased in SO_3 and retention of sulphur in the ash. What level of understanding do we have on this issue?

42. Improvement of sulphur capture in FGD operation has been reported when firing coal under oxy-firing conditions. To what extent can we verify these results?

43. What is the behaviour of mercury and other trace elements in coal when fired in an $O_2/CO_2/H_2O$ atmosphere?

44. What are the level of PM_{10} and $PM_{2.5}$ when firing coal under oxy-firing condition?

45. Some pilot scale studies have reported mercury emission reduction, is this so?

46. Given our understanding regarding corrosion and SO_2/SO_3, will the oxy-fuel firing techniques be limited to low sulphur coal?

Slagging and Fouling

47. What is the behaviour of ash under $O_2/CO_2/H_2O$ atmosphere in terms of slagging and fouling propensity? Will the ash deposition characteristics differ to the air-fired system?

48. What are the properties – composition and size distribution - of the ash? Is it similar to ash composition of the air fired system?

Effect on Furnace and Boiler Material

49. What are the effect of $O_2/CO_2/H_2O$ environment to the metal and refractory materials and its propensity of high temperature corrosion?

II. PRACTICAL PLANT OPERATION AND SAFETY ISSUES

50. For plant retrofit, the challenge will be on how to minimise air ingress. One possible solution is to operate boiler with a slight positive pressure – in this case what are the different safety issues to be considered when boiler is operated under such condition?

51. What operational factors must be established in demonstration, including O_2 supply for load following?

52. What factors should be considered in terms of starting up and turn down operation in the point of view of safety especially in the handling of oxygen?

53. For plant safety, what kinds of safety interlock must be considered – especially in the oxygen supply side in cases where problem occur involving the recirculation fan?

54. For plant retrofit, what is optimum operating temperature of the flue gas that will not reduce the performance of the ESP or bag filter?

55. For plant retrofit, what are the different issues to be considered during the operation of soot blowers especially when handling a lower volume of flue gas?

56. Handling of recycled flue gas for coal transport – What level of flue gas treatment necessary to prevent any disruption of the fuel supply side? – ie. effect of higher moisture content of the transport gas.

III. O_2 PRODUCTION and CO_2 PROCESSING & COMPRESSION

The purity of the oxygen required and the level of final treatment of flue gas (ie. in terms of CO_2 purity) will strongly depend on the target storage or final utilisation of the flue gas captured. On this basis, consideration should be made based on assumptions that flue gas captured could be used in the following cases:

- for Enhanced Oil Recovery (EOR) and Enhanced Gas Recovery (EGR)
- for Enhanced Coal Bed Methane Recovery (ECBM)
- for Storage in Saline Aquifier
- for Geological Storage or Ocean Storage

57. What is the dynamic matching between oxygen production,. boiler operation and CO_2 processing? What is the process bottle neck when operating oxyfiring unit under higher load change?

58. What is the optimum purity of oxygen required to reduce electric consumption?

    58.1. Is there any other possible utilisation for cold waste N_2 produced?

    58.2. Assuming oxygen will be produced via cryogenic process, what are the optimum arrangements for columns to produce the necessary O_2 required to achieve minimum operation and capital cost?

59. What level of backup supply of oxygen is necessary to ensure smooth operation of the power plant?

60. What is the purity of CO_2 required for transport and further usage/storage?

    60.1. Is there a CO2 purity required for compression? Is a binary equilibrium approximation suitable for this estimation?

    60.2. To what extent it is necessary to remove non-condensable gas from the flue gas stream?

    60.3. To what level dehydration of the flue gas is necessary to prevent any corrosion within the transport line?

    60.4. To what extent should SO_2 / NOx and other pollutant to be separated from the final flue gas stream?

Note:

We would like to acknowledge the comments provided by Prof. Terry Wall and Mr. Keiji Makino in preparing this document.

****

GENERAL SURVEY

To the participants / interested parties:

The general questions prepared in this document are numbered accordingly. we would be glad to know what you think is important. What is the priority area for research?

Please return this survey to Stanley Santos at

stanley@ieaghg.org

or bring this piece of paper along with you when you're in Cottbus.

****

What are the TOP 10 questions / issues you think should be the highest priority? – Please list down the question number.

If you have any other specific questions that you would like to include please feel free to send it over to the workshop secretariat.

Other questions / issues that you would like to raise?

Name:		Organisation:	

This page is intentionally left blank

APPENDIX 4

Poster Contribution

1st International Oxy-Combustion Workshop
Cottbus, Germany
29th – 30th November 2005

- **Oxy-Fuel Combustion Studies for CO_2 Capture R&D Programme in Korea**
  Dong-Soon Noh*, Kook-Young Ahn, and Chang-Ha Lee
  * Korea Institute of Energy Research, South Korea

- **Oxyfuel Combustion Technology for CO_2 Capture at Power Plants**
  Anand B. Rao, Michael B. Berkenpas and Edward S. Rubin
  Department of Engineering and Public Policy, Carnegie Mellon University, Pittsburgh, USA

- **Clean Energy Systems Inc. Demo Project - Summary and Update (Nov. 2005)**
  Keith Pronske
  Clean Energy System Inc., California, USA

- **Oxyfuel Process for Hard Coal with CO_2 Capture – ADECOS Project First Results**
  Prof. Alfons Kather
  Hamburg University Of Technology, Hamburg, Germany

This page is intentionally left blank

Inaugural Workshop

International Oxy-Combustion Research Network

Vattenfall Europe Mining and Generation AG Head Office
Cottbus, Germany

29th and 30th November 2005

Poster Contribution

Oxy-Fuel Combustion Studies for CO_2 Capture R&D Programme in Korea

by:

Dong-Soon Noh[1]*, Kook-Young Ahn[2], and Chang-Ha Lee[3]

[1] Korea Institute of Energy Research,
71-2 Jang-dong, Yuseong-gu, Daejeon 305-343, Korea

[2] Korea Institute of Machinery and Materials,
171 Jang-dong, Yuseong-gu, Daejeon, 305-343, Korea

[3] Department of Chemical Engineering, Yonsei University,
Shinchon-dong, Seodaemun-gu, Seoul, 120-749, Korea

This page is intentionally left blank

Inaugural Workshop of the International Oxy-Fuel Combustion Network
Participants' Poster Contribution

29th – 30th November 2005
Cottbus, Germany

Oxy-Fuel Combustion Studies for CO_2 Capture R&D Programme in Korea

Dong-Soon Noh[1*], Kook-Young Ahn[2], and Chang-Ha Lee[3]

[1] Korea Institute of Energy Research,
71-2 Jang-dong, Yuseong-gu, Daejeon 305-343, Korea

[2] Korea Institute of Machinery and Materials,
171 Jang-dong, Yuseong-gu, Daejeon, 305-343, Korea

[3] Department of Chemical Engineering, Yonsei University,
Shinchon-dong, Seodaemun-gu, Seoul, 120-749, Korea

ABSTRACT

In this paper the latest developments of high performance oxy-fuel combustion reheating furnace system including oxy-burner and high purity O_2 generation is presented. The flame characteristics of CH_4/O_2 turbulent diffusion flames have been investigated in the present study with small amount of nitrogen doped to simulate oxy-fuel combustion in the industrial furnace. Results show that flame length and shape can be controlled by varying flow conditions. NOx formation was decreased by the high velocity injection of fuel or oxygen, which was made possible by oxy-fuel combustion due to enhanced flame stability. The high velocity injection enhances the entrainment of product gas to flame zone, decreasing flame temperature and resulting in NOx decrease, which is called as in-furnace recirculation effect. The heating performance of the oxy-fuel combustion were also investigated experimentally by using furnace simulator and compared with those of air-fuel combustion. A three-bed pressure vacuum swing adsorption (PVSA) process, combined equilibrium separation with kinetic separation, was developed to overcome the 94% O_2 purity restriction inherent to air separation in the adsorption process. To produce 97+% and/or 99+% purity O_2 directly from air, the PVSA process was executed at 0.33-0.45 to 2.5 atm. In addition, the effluent gas from the CMS bed to be used for O_2 purification was backfilled to the zeolite 10X bed to improve its purity, recovery and productivity in bulk separation of the air. A non-isothermal dynamic model was applied to predict the process dynamics. Using the LDF model for the equilibrium separation bed and a modified LDF model for the kinetic separation bed, the dynamic model was able to accurately predict the results of the experiment.

INTRODUCTION

Industrial furnaces such as reheat furnace, melting furnace and so on shares about 12% of domestic energy consumption in Korea. Enhancement of thermal efficiency of reheat furnaces is an important issue in conjunction with global warming and fuel economy. Oxy-fuel combustion, which utilizes oxygen as an oxidizer instead of conventional air, has aroused considerable interest as a new industrial combustion technology. Energy efficiency can be greatly increased by oxy-fuel combustion since the unnecessary heating of nitrogen in air will be eliminated. Because

* Corresponding author: E-mail: dsnoh@kier.re.kr

of the exclusion of nitrogen in the oxidizer, the volume of exhaust gas significantly decreases and the NOx formation can be eliminated theoretically, but not practically. This will be explained in the following paragraph. Further advantages such as higher temperature, faster flame propagation speed and better flame stability are expected from the oxy-fuel combustion.

The oxy-fuel combustion, which will facilitate CO_2 capture from exhaust, is reported to be one of the most effective and active ways to cope with the future CO_2 regulation internationally agreed on by the 1997 Kyoto Protocol. However, the high cost of oxygen separation has been a main roadblock in the development of the oxyfuel combustion technologies. Pollutant emissions such as CO and NOx caused by high flame temperatures have also been a significant problem. NOx problems arise since it is impossible to totally eliminate nitrogen even with the oxyfuel combustion. The two main sources of nitrogen are the inherent nitrogen in separated oxygen and the air entrainment through leakages or the load inlet/outlet in furnaces.

As the air separation technologies improve and the cost of oxygen diminishes, the oxyfuel burners recently have started to be applied for high-temperature industrial processes such as glass melting, steel refining and iron foundry to improve productivity and save fuel consumption. As the applications increase, the reduction of NOx emissions becomes important requirement in many burner designs. Various methods such as flue gas recirculation (FGR) and staged combustion have been developed and applied to reduce temperature and enhance temperature uniformity.

For the meantime, the primary concerns in the steel industry are productivity, energy efficiency and reduced emissions. These demands can and indeed have been satisfied by the use of oxy-fuel combustion in a wide range of both batch and continuous type furnaces and, O_2/pulverized-coal combustion is considered as a cost-effective CO_2 capture technology in power plant as well.

EXPERIMENT

Burner Development

The apparatus consisted of a combustor, a combustion chamber, flow controlling system and a gas analyzer. The combustor was a typical normal co-flow burner with fuel being supplied through the inner nozzle. The fuel was chemically-pure grade (> 99.9 %) methane and the oxidizer was oxygen doped with small amount of nitrogen. Nitrogen was added to simulate industrial combustion system using air separation unit. The resulting NOx concentration can be the indicator of maximum flame temperature. The flow rates of methane, oxygen and nitrogen were fixed at 50 lpm (0.03 MW), 110 lpm (10 % excess O_2) and 3.3 lpm (3 % of O_2), respectively. The flow velocities of fuel and oxidizer were varied by changing the inner and the outer nozzle diameters.

A cylindrical quartz tube with 50 cm i.d. was used as a combustion chamber for visualization. Emissions such as CO and NOx were measured by a gas analyzer (Greenline MK-2) using a water-cooled sampling probe.

Heating Performance Test

Oxy-natural gas burner was used and the heating performance was tested with small scale batch furnace system in the present study. Figure 1 shows a schematic diagram of the furnace simulator, and real view of simulator.

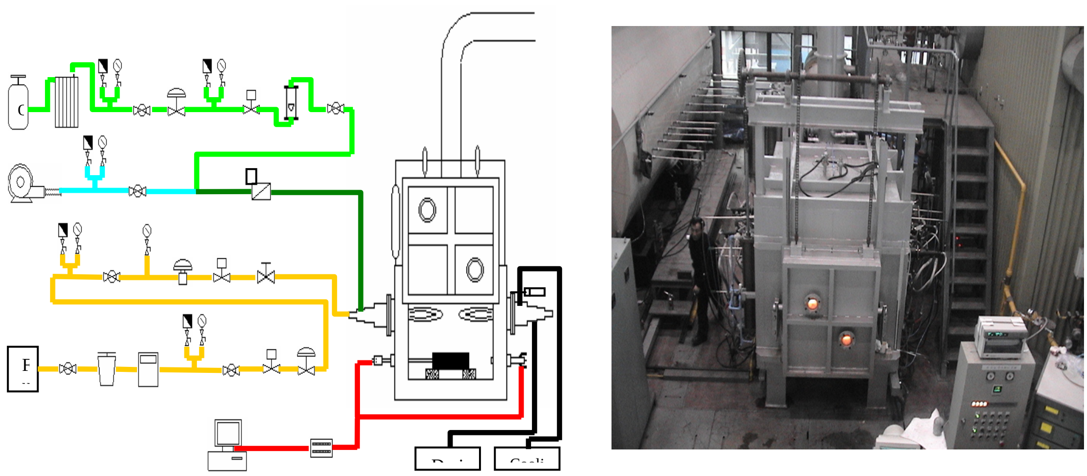


Figure 1. Schematic of the furnace simulator and its actual view

Four burners were installed on both side wall (two burners in each for horizontal firing). The burner used here was designed to use oxygen only and/or air as an oxidant respectively by delicate control of fuel nozzle position. The fuel nozzle is located in center and the oxidant flows through the outer annulus. By positioning the burner eccentrically, about 70cm away from the center of burner block, the relative burner location to the steel can be changed by rotating the burner block. Methane base d town gas was used as a fuel and liquid oxygen was used as an oxidant.

Measurements were performed on the steel materials (0.6 tons) and furnace inside temperature, and flue gas properties. The temperature was measured using R-type thermocouples for the inside of furnace and K-type for steel, and flue gas was measured by using a gas analyzer through the middle of exhaust duct with sampling probe.

A Three-Bed PVSA Process for High Purity O_2 Generation

A schematic diagram of the three-bed PVSA unit is shown in Figure 2. Zeolite 10X (Baylith, WE-G 639) and CMS (Takeda Chem., 3A) were used as adsorbents in the PVSA experiments. Prior to the experimental runs, the zeolite 10X was regenerated at 613K overnight and the CMS at 423K. Each activated adsorbent bed was filled with pure O_2 (99.9+%) to prevent contamination from the outside air. Prior to running each experiment, the adsorption beds were vacuumed for 2 hours. As an initial condition, the PVSA experiments were conducted at the bed saturated with pure O_2 (99.9+%) under the same level of adsorption pressure as used throughout the experiment. The temperatures of the feed, bed, and surroundings were kept in the range of 297K to 300K during the experiments. The ternary mixture (N_2/O_2/Ar; 78:21:1 vol.%, DaeSung Ind. Gas) was used as feed gas for the PVSA experiments.

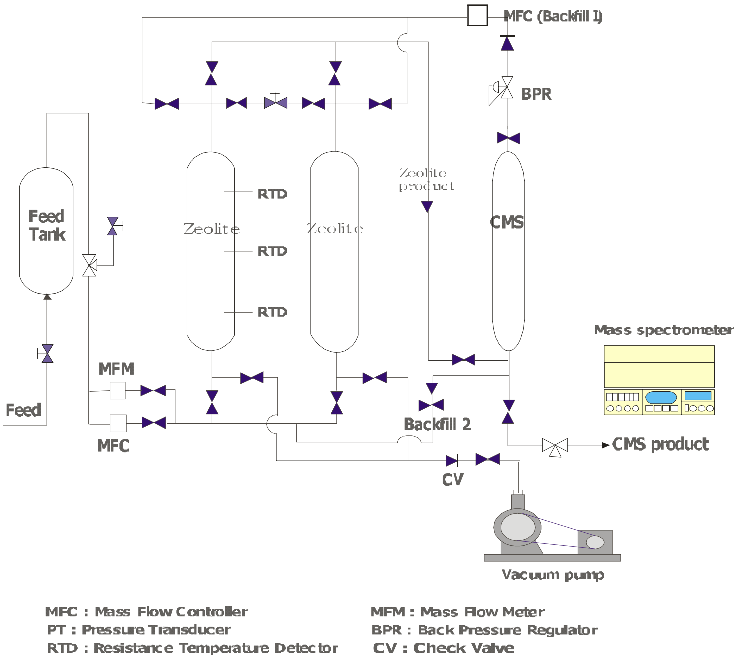


Figure 2. A schematic diagram of the three-bed PVSA unit

RESULTS AND DISCUSSION

Behavior of Oxy-fuel Flames by Varying Flow Velocities

Figure 3 shows the oxy-fuel flame images with increasing coflow oxidizer velocity at u_f = 40 m/s. It is to be noted that flame stabilization is hardly achieved with either fuel or air velocities over 10 m/s when air is use as oxidizer. As shown in Figure 3, the flames were attached to the fuel nozzle without a swirler or a quarl demonstrating that oxy-fuel combustion significantly enhances flame stabilization, which can be attributed to the 10-times higher flame propagation speed for oxyfuel flames than air-fuel flames.

Figure 4 shows the variation of flame lengths by varying fuel and oxidizer velocities. Flame length decreases as either fuel or oxidizer velocity increases due to increased turbulent mixing effect. Flame lengths were reported to be well correlated with turbulent kinetic energy. As fuel or coflow velocity increases, yellowish flame luminosity from soot particles decreases as well as flame length and volume as shown in Figure 3 due to the decrease of residence time. Measured CO level was under 100 ppm for all cases meaning that the reduction of flame length does not affect overall combustion (CO even decreases with increasing co-flow velocity as shown in Figure 5.).

In-Furnace Recirculation Effect

Figure 5 shows the NOx concentration with increasing coflow velocity at u_f = 40 m/s. NOx concentration monotonically decreases as coflow velocity increases while it was expected to decrease since the flame volume decreases. This result can be explained by *in-furnace recirculation effect* as drawn in Figure 6. Oxy-fuel combustion made high velocity injection

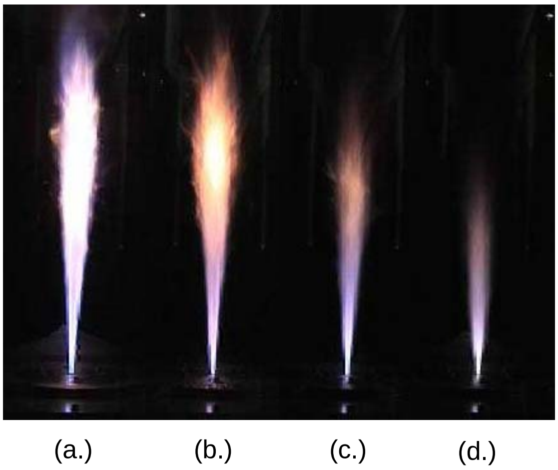


Figure 3. Flame images with increasing coflow velocity; (a) uo = 8.7, (b) 20.0, (c) 40.2 and (d) 59.6 m/s

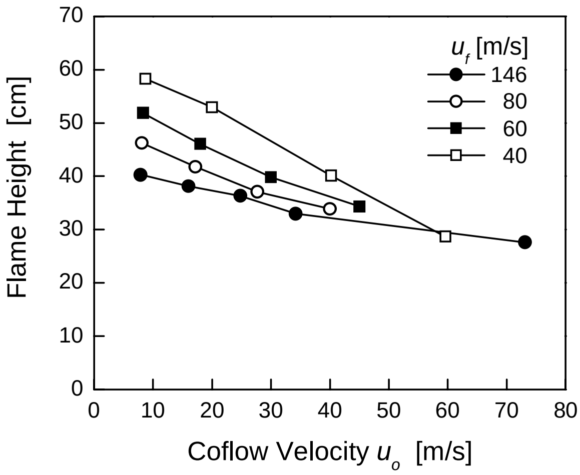


Figure 4. Variation of flame length with increasing oxidizer velocity.

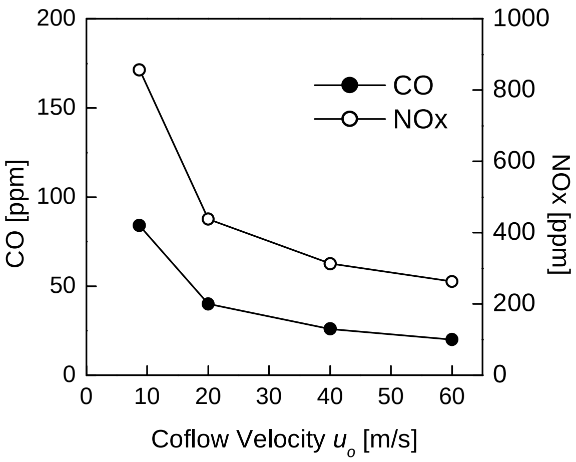


Figure 5. Variation of CO and NOx concentration with increasing oxidizer velocity.

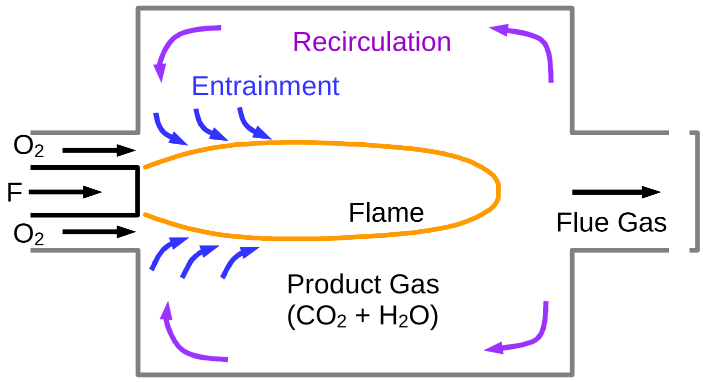


Figure 6. Schematic diagram of in-furnace recirculation effect.

possible, which entrains the significant amount of product gas in furnace recirculated to flame. Thus, NOx decreases with increasing flow velocities since adiabatic flame temperature decreases by the entrainment.

This effect can be applied to DOC (Dilute Oxygen Combustion) and high velocity burners. In order to confirm the in-furnace recirculation effect, the inner fuel nozzle extrusion was varied to enhance or block the product-gas entrainment. As shown in Figure 7, NOx was increased by the nozzle intrusion and decreased by the nozzle extrusion from the burner surface, confirming the in-furnace recirculation effect.

Based on these experimental results, scaled-up 300kW oxy-fuel combustors were tested as shown in Figure 8 and four 30kW oxy-fuel burners were installed in steel reheating furnace simulator.(Figure 1)

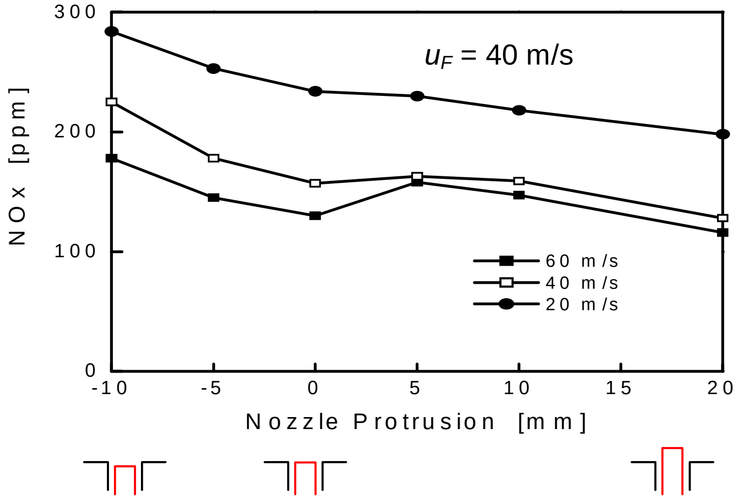


Figure 7. Variation of NOx concentration by varying nozzle extrusion.

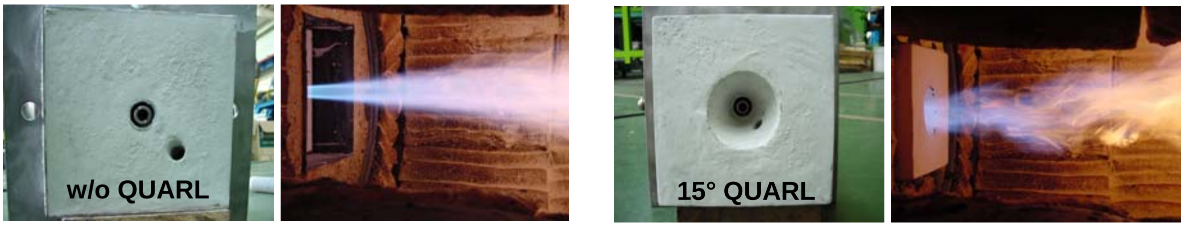


Figure 8. 300kW oxy-fuel burners and flames

Steel Reheating Performance

For the same burner position, it is easily expected that the more fuel rate, the higher temperature. In other hands, for the same fuel rate, there is no influence of burner locations in reaching the 1200 °C of steel temperature. It is because the radiation heat transfer in oxy combustion is one of the main effects on raise of steel temperature.

Figure 9 shows temperature profiles according to oxygen and air combustion for the same test conditions. Oxy-fuel combustion takes 310 minute to raise the steel temperature up to 1200°C, while air-combustion takes 800 minute. It is about 61% reduction of heating time, which related directly with energy saving and efficiency. At the aspects of operating cost, in addition, the fuel cost is about $58.2 for air-fuel combustion. On oxy-fuel combustion, however, its total costs are $44.5 ($22.4 for fuel and $22.1 for oxygen) based on current market price in Korea. It brings not only about 23% reduction of operation cost, but also higher productivity compare to air-fuel combustion.

As can be presumed, measured CO_2 concentration in flue gas leaving the furnace was about 89% and nearly 100% after condensation of water vapor in case of oxy-combustion. Higher CO_2 concentration provides a relatively cost effective CO_2 capture and possibility of flame control by CO_2 recirculation for various furnace operations.

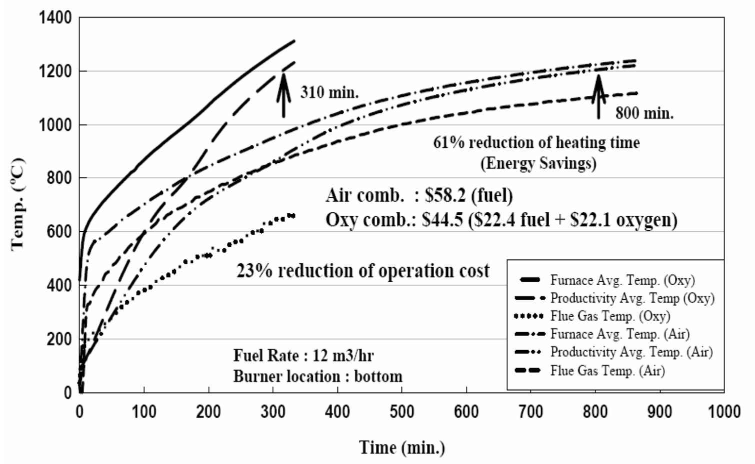


Figure 9. The effect of oxidants on temperature profiles

A THREE-BED PVSA PROCESS

Effect of Feed Composition

First of all, the study about 2-bed PSA process to purify oxygen was performed before 3-bed PVSA study was developed. As reported in lots of studies [5-6], most of the O_2 PSA systems using a zeolite molecular sieve showed a result of 90-93% purity with 50+% recovery or 95+% purity with below 30% recovery. Since various concentrations of nitrogen were included with the product from the O_2 generation systems, there was a need to study the effect of a nitrogen composition in the feed gas on an O_2 purification PSA process. In order to compare the effect of the composition of nitrogen impurity on the total cyclic performance, three different feeds containing 0%, 1%, and 6% nitrogen were applied, which the amount of Ar in the feed was fixed at 4 vol.%.

Figure 10 show the effect of nitrogen impurity on O_2 purity and recovery. The maximum purity of O_2 was 99.8% or higher. The O_2 purity was slightly decreased as increasing amounts of nitrogen impurities in feed, while O_2 recovery became higher with an increase of nitrogen impurities in feed.

Cyclic Performance of PVSA I with a Single Blowdown/Backfill step

Figure 11 shows the pressure variation profiles at bed end under the cyclic steady-state of PVSA I . Since the effluent from the zeolite 10X bed during the AD step at 2.5 atm was supplied as feed gas for the PR and AD steps of the CMS bed, the CMS bed was pressurized to 1.6 atm. The effluent from the AD step of the CMS bed was backfilled into the other zeolite 10X bed. Therefore, the pressure of the zeolite bed increased slightly after the VU step (Figure 3(a)). It is noteworthy that the CMS bed underwent two cycles for every one cycle of the zeolite bed since each of the zeolite beds and the CMS bed was tied to the same cycle time.

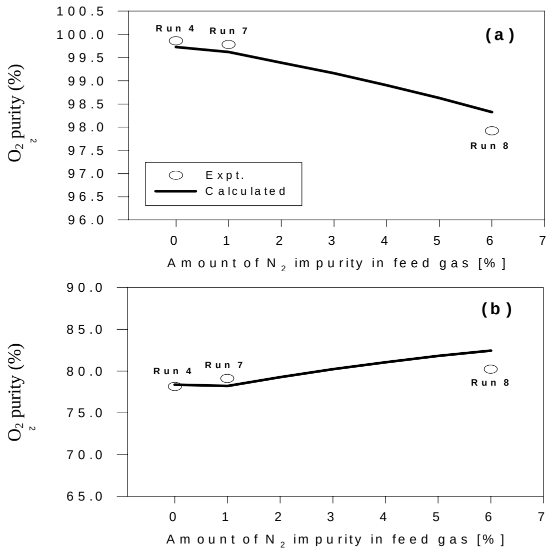


Figure 10. The effect of nitrogen impurity on O_2 purity and recovery

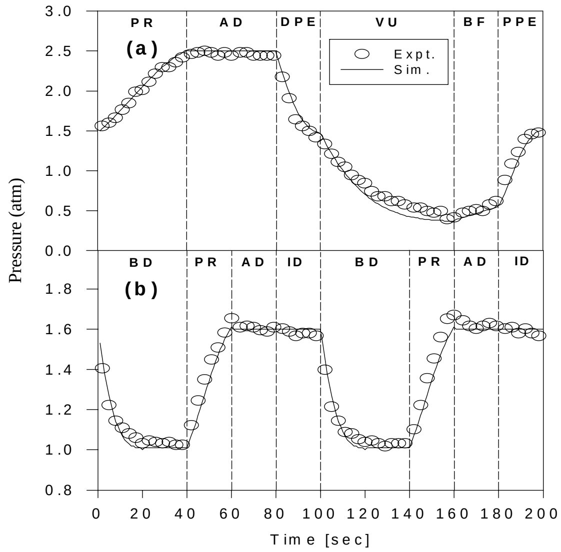


Figure 11. The pressure variation profiles at bed end

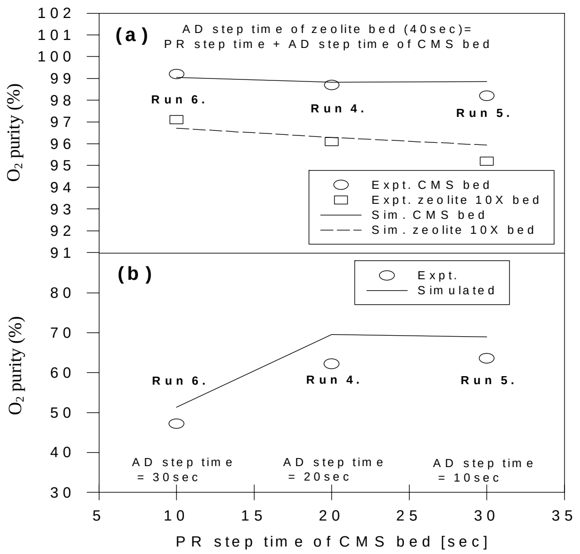


Figure 12. Effect of Adsorption step time in the CMS bed on performance of PVSA I

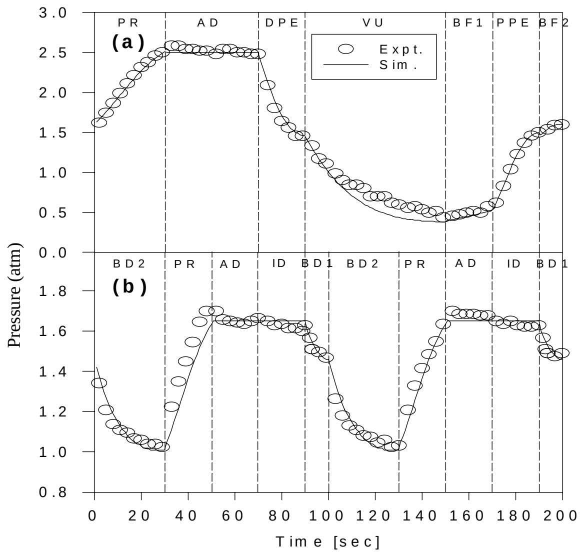


Figure 13. The pressure variation profiles at bed end

Effect of Adsorption StepTtime in the CMS Bed on Performance of PVSA I

As shown in Figure 12(a), as the AD step time of the CMS bed decreased from 30 to 10sec (the PR step time of the CMS bed increased from 10sec to 30sec), the purity of both the zeolite 10X and the CMS beds decreased linearly because of the reduced amount of backfill gas in the zeolite bed and the diminished time for impurity removal in the CMS bed. The effect of the AD step time of the CMS bed on the purity of each bed was slightly greater in the zeolite bed than in the CMS bed. As shown in Figure 12(b), with a decrease in the AD step time, O2 recovery substantially increased to 85% because the extended PR step time of the CMS bed led to increased adsorption pressure in the CMS bed.

Cyclic performance of PVSA II with double blowdown / backfill steps

Figure 13 shows the pressure variation profile during PVSA II. Unlike PVSA I in Figure 11, an additional BF step (BF2) was added in the zeolite 10X bed and two consecutive BD steps (BD1 and BD2) were applied to the CMS bed. The effluents from the AD and BD1 steps in the CMS bed were used to partially pressurize the zeolite 10X bed at the BF1 and BF2, respectively.

Effect of Adsorption Step Time in the CMS bed on performance of PVSA II

As shown in Figure 14(a), when the AD step time of the CMS bed increased from 10sec to 30sec, the purity of both the zeolite 10X and CMS beds increased linearly, similar to the results noted in Figure 12(a). Consequently, oxygen with 99.2% purity was produced at the AD step time of 30 sec because a greater amount of impurities had been removed from the CMS bed and a greater amount of O_2 had been supplied to the zeolite bed through the BF1 step. Therefore, the O_2 purity of the zeolite 10X bed also increased to 97% under this AD step time. However, as shown in Figure 14(b), the recovery diminished as the PR step time decreased because the decreased PR step time of the CMS bed led to a lower adsorption pressure in the bed.

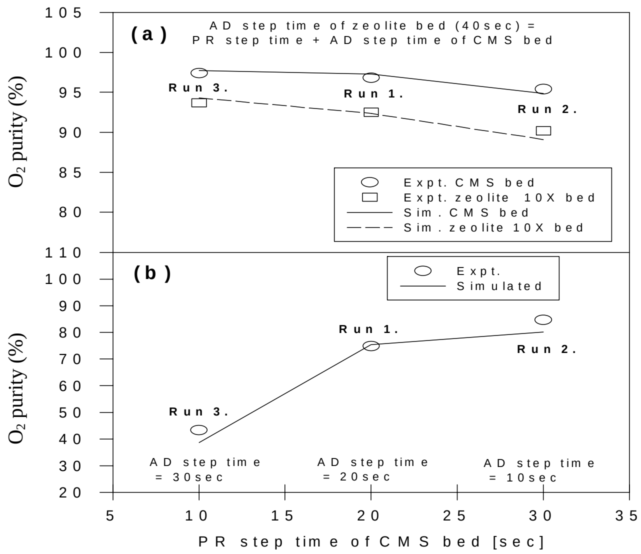


Figure 14. The effect of adsorption step time in the CMS bed on performance of PVSA II

Compared with the results of PVSA I, it is clear that PVSA II can produce higher purity of O_2 than PVSA I under the same conditions in cyclic time, pressure and feed flow rate.

CONCLUSION

1.) The flame characteristics of CH_4/O_2 turbulent diffusion flames have been investigated by varying flow conditions in order to provide design factors of oxy-fuel burners. The results are summarized as follows:

- Flame stability was significantly enhanced by oxy-fuel combustion, which makes high velocity injection possible.

- Flame length was decreased with increasing flow velocities caused by the increased turbulent mixing.

- Oxy-fuel combustion with high velocity injection can facilitate the entrainment of product gas in furnace to flame, causing the decrease of flame temperature and NOx generation.

2.) The heating performance of the oxy-fuel combustion were investigated experimentally by using furnace simulator and compared with those of air-fuel combustion. The following results were obtained.

- Based on this furnace simulator, the reaching time of 1200oC on steel materials has about 61% fuel savings compared to air-fuel combustion and 23% reduction of operation cost. It can be noted that the reduction of operation cost is likely to dependant on the ratio of oxygen cost/fuel cost.

- Further substantial dilution by combustion products (CO2 recirculation) is also essential to control the flame and furnace temperature in order to extend the technology to the industrial furnace applications and oxy-coal combustion power plant.

3.) The PVSA process overcame the purity limit of common adsorption processes using zeolites because of the one or two-stage backfill steps supplied from the CMS bed. Thus, PVSA could produce an O_2 purity of 95.4-99.2% with a recovery of 43.4-84.8% through the CMS bed. The increased AD step time of the CMS bed led to an increase in O_2 purity and a decrease in O_2 recovery in the PVSA process. However, because more highly concentrated O_2 was supplied from the zeolite bed in PVSA II rather than in PVSA I, the CMS bed in PVSA II could be kept fairly clean after the production step, regardless of the applied AD step time in the CMS bed. Therefore, the CMS bed had more favorable conditions for the purification of feed in PVSA II. It is noted that the amounts of N_2 in the product were in the level of 4000-5000ppm at the PVSA I and several tens of ppm at the PVSA II..

FUTURE WORKS

- CO_2 Recirculation Assimetric O2 Burner for Industrial Furnace Applications
  - Burner/furnace design and system integration

- Field Demonstration of Oxy-Fuel Combustion Reheat Furnaces
  - Batch furnace (50ton-steel/charge), Continuous type furnace (10ton/hr)

- O_2/ CO_2 – Coal Combustion for CO2 Capture in PC Power Plant
  - Low NOx O2/CO2-Coal combustion burner & control

ACKNOWLEDGMENTS

The authors wish to thanks the financial support for this research provided by Carbon Dioxide Reduction and Sequestration (CDRS) Research Center for the Ministry of Science and Technology (MOST), Korea.

REFERENCES

[1.] C.E. Baukal, "Industrial Burners Handbook", CRC Press, 2004.
[2.] J.C. Sautet, L. Salenty and M. DiTaranto, Int. Comm. Heat Mass Transfer, 28(2), (2001) 277.
[3.] H.K. Kim, S.M. Lee, H.S. Kim and K.Y. Ahn, KOSCO Journal, (2004) Submitted
[4.] Brown, T. Ekman and C. L. Axelsson, "The Development and Application of Oxy-fuel technology for Use in Heating Furnace Applications", AFRC/JFRC/IEA 2001 Joint International Combustion Symposium, 2001.
[5.] Delabroy, et al. "Oxy-combustion for Reheat Furnace", AFRC/JFRC/IEA 2001 Joint International Combustion Symposium, 2001.
[6.] Marin, et al., "Oxygen Enrichment in Boilers", AFRC/JFRC/IEA 2001 Joint International Combustion Symposium, 2001.
[7.] T. Suwa, "Overview of Application Technologies using Oxy-Fuel Combustion in Japan", AFRC/JFRC/IEA 2001 Joint International Combustion Symposium, 2001.
[8.] R. Kumar, Sep. Sci. and Tech., 31, (1996) 877.
[9.] S. U. Rege and R. T. Yang, Adsorption, 6, (2000) 15.
[10.] J.-G. Jee, M.-B. Kim, and C.-H. Lee, Chem. Eng. Sci., 60, (2004) 869.
[11.] Y.-S. Bae and C.-H. Lee, Carbon, 43, (2005) 95.
[12.] J.-G.. Jee, J.-S. Lee, and C.-H. Lee, Ind. Eng. Chem. Res., 40, (2001) 3647.
[13.] D. M. Ruthven, S. Farooq, and K. S. Knaebel, "Pressure Swing Adsorption," VCH, New York, 1994.

This page is intentionally left blank

Inaugural Workshop

International Oxy-Combustion Research Network

Vattenfall Europe Mining and Generation AG Head Office
Cottbus, Germany

29th and 30th November 2005

Poster Contribution

Oxyfuel Combustion Technology for CO_2 Capture at Power Plants

by:

Anand B. Rao, Michael B. Berkenpas and Edward S. Rubin

Department of Engineering and Public Policy,
Carnegie Mellon University, Pittsburgh, USA

IEA GREENHOUSE GAS R&D PROGRAMME

This page is intentionally left blank

Oxyfuel Combustion Technology for CO_2 Capture at Power Plants

Anand B. Rao, Michael B. Berkenpas and
Edward S. Rubin

Department of Engineering and Public Policy,
Carnegie Mellon University, Pittsburgh, USA

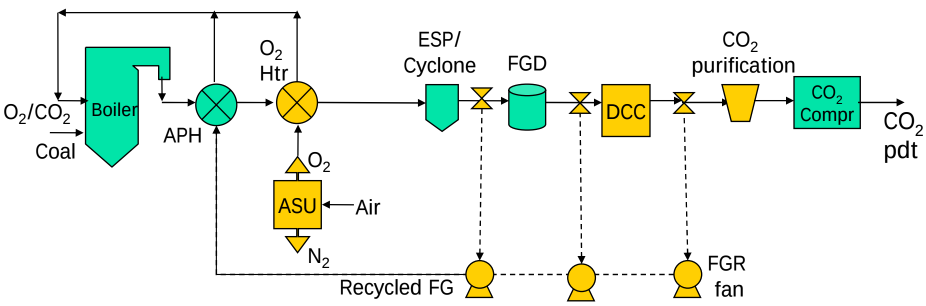
First Workshop for the Oxy-Fuel Combustion Network,
Cottbus, Germany
November 29-30, 2005

Process Configuration Options

- Steam cycle: Sub-/ Super-/ Ultra-Super- Critical
- Oxygen generator: Cryogenic
- Flue gas recycle (FGR): Yes or No
  - If FGR: Wet recycle or Dry recycle?
- Particulate removal: ESP/ cyclone/ bag house
- Flue gas cooler: Yes or No
  - If FGR and FG cooler: Where should it be located?
- Need for FGD? Location?
- Need for SCR?
- Need for CO_2 purification system?
- Heat integration features: APH, O_2 heater, use of N_2

2

Proposed Configuration: IECM-CS



3

Process Performance Parameters

Parameter	Typical	Range
• Oxygen purity (%v/v)	95	90-100
• Excess air (%)	5	0-19
• Air leakage (%)	2*	0-19
• Flue gas recycle ratio	0.7	0-0.9
• FGR fan pressure head (psi)	0.2	
• FGR fan efficiency (%)	75	
• CO_2 product pressure (psig)	2000	
• CO_2 product purity (%w/w)	97	95-99

4

Process Performance Results

Performance indices:
- Boiler efficiency
- NO_x emission factor
- Overall CO_2 removal
- Overall SO_2 removal
- Overall NO_x removal
- Overall dust removal

Flow rates:
- Oxygen supply from ASU
- Recycled flue gas
- CO_2 product
- Emissions (if any)

Energy requirement:
- ASU
- FGR fan
- CO_2 purification
- CO_2 compression

Process Cost Parameters

Process Area Costs

New:
- Boiler modification
- FGR fan
- FGR ducting
- APH/ O_2 heater
- CO_2 purification system

Existing (in IECM):
- ASU
- CO_2 compressor

O&M Costs
- Operating Labor
- Maintenance Labor
- Admin./Support Labor
- Maintenance Materials

- Chemicals Cost
- Waste Disposal Cost
- Water Cost
- Power Cost*
- CO_2 Transport Cost
- CO_2 Storage Cost

Oxyfuel option in IECM-CS: Current Status

- Basic performance and cost model is ready.
- The module has been integrated with the IECM-CS modeling framework.
- Case studies and model applications are in progress.

Case Study

- An on-going case study of CO_2 retrofit options for existing coal-fired plants is presented here.
- The reference plants have been characterized on the basis of analysis of US power plants database.

7

Baseline Assumptions

Reference Plant (Sub-critical)	**R1**	**R2**
Gross Plant Size	250 MW	500 MW
Fuel Type	0.6%S Bit	2.1%S Bit
Coal HHV (MJ/kg)	30.4	30.8
Net HHV Efficiency (%)	32.1	32.7
Capacity Factor (%)	**62**	**77**
Particulate Control	ESP	ESP
SO_2 Control	-	FGD
SO_2 Control Efficiency	-	~80%

Also: age of both plants ~40 years (capital cost of the plants is completely paid off);
coal cost = $1.2/GJ;
fixed charge factor = 0.148;
all costs in constant 2002 US$

8

CO_2 Retrofit Cases

Case	Boiler	η_{net} (%)	FGD	η_{SO2} (%)	CO_2 Capture System	η_{CO2} (%)
R1(ref)	old, sub		-	-	-	-
A	old, sub		new	99	MEA	90
B	*new, super*		new	99	MEA	90
C1	old, sub		-	-	OXYFUEL	90
C2	old, sub		-	-	OXYFUEL	*100**
D1	*new, super*		-	-	OXYFUEL	90
D2	*new, super*		-	-	OXYFUEL	*100**

sub= Sub-critical; super = Super-critical;
old = part of existing plant; new = installed as a part of the CO_2 retrofit option;
MEA = monoethanolamine based CO2 scrubber system;
OXYFUEL = oxyfuel combustion with flue gas recycle system for CO_2 capture
**Oxyfuel combustion cases with zero emission to atmosphere, all the flue gas (predominantly CO_2) is assumed to be compressed for transport and disposal*

CO_2 Retrofit Cases (contd.)

Case	Boiler	η_{net} (%)	FGD	η_{SO2} (%)	CO_2 Capture System	η_{CO2} (%)
R2(ref)	old, sub		old	80	-	-
E	old, sub		upgrade	99	MEA	90
F	*new, super*		upgrade	99	MEA	90
G1	old, sub		old	80	OXYFUEL	90
G2	old, sub		old	80	OXYFUEL	*100**
H1	*new, super*		old	80	OXYFUEL	90
H2	*new, super*		old	80	OXYFUEL	*100**

sub= Sub-critical; super = Super-critical;
old = part of existing plant; new/upgrade = installed/upgraded as a part of the CO_2 retrofit option;
MEA = monoethanolamine based CO2 scrubber system;
OXYFUEL = oxyfuel combustion with flue gas recycle system for CO_2 capture
**Oxyfuel combustion cases with zero emission to atmosphere, all the flue gas (predominantly CO_2) is assumed to be compressed for transport and disposal*

Performance and Cost Results

Case	Net Power (MW)	Emission rate gCO_2/kWh	TCR ($/kW)	COE ($/MWh)	CO_2 avoidance cost ($/tonne CO_2)
R1(ref)	253.1	969	0	22.3	
A	172.7	143	890	70.9	58.8
B	*189.9*	102	1286	69.0	53.7
C1	167.3	139	1527	84.6	75.1
C2	168.7	0	1502	83.6	63.2
D1	*185.7*	98	1746	78.6	64.7
D2	*186.8*	0	1730	78.0	57.4

Performance and Cost Results (contd.)

Case	Net Power (MW)	Emission rate gCO_2/kWh	TCR ($/kW)	COE ($/MWh)	CO_2 avoidance cost ($/tonne CO_2)
R2(ref)	496.5	973	0	20.7	
E	348.7	139	589	51.9	37.5
F	*377.5*	105	1030	52.3	36.4
G1	348.9	131	1332	64.7	52.2
G2	351.7	0	1298	63.5	44.0
H1	*377.6*	99	1650	63.6	49.1
H2	*379.9*	0	1625	62.8	43.3

Inaugural Workshop

International Oxy-Combustion Research Network

Vattenfall Europe Mining and Generation AG Head Office
Cottbus, Germany

29th and 30th November 2005

Poster Contribution

Clean Energy Systems Inc. Demo Project

Summary and Update (November 2005)

by:

Keith Pronske

Clean Energy System Inc.
11330 Sunco Drive, Suite A
Rancho Cordova, CA 95742-7500

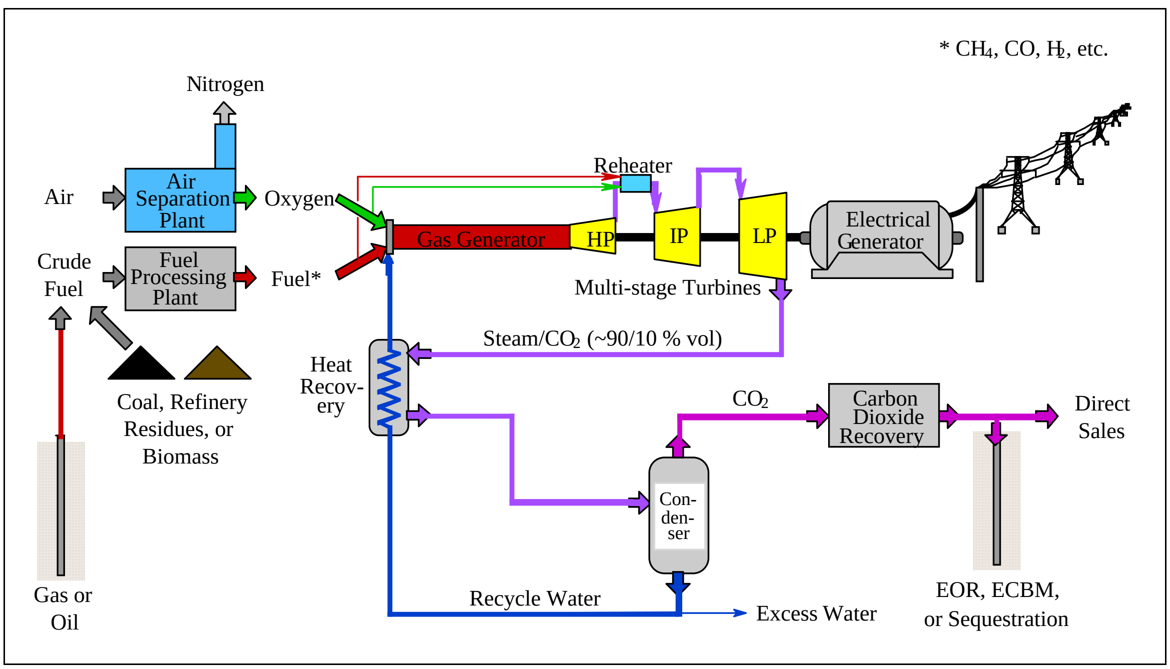
This page is intentionally left blank

Clean Energy Systems, Inc.
Summary and Update
November 2005

www.cleanenergysystems.com

Clean Energy Systems, Inc. (CES) is developing zero-emissions fossil-fueled power generation technology, integrating proven aerospace technology into conventional power systems. The core of CES' process involves replacing steam boilers and flue gas cleaning systems with "gas generator" technology adapted from rocket engines. The gas generator burns a combination of oxygen and a gaseous hydrocarbon fuel to produce a mixed gas of steam and carbon dioxide at high temperature and pressure, which powers conventional or advanced steam turbines. High efficiencies are obtained for utility-sized power plants, but without any atmospheric emissions. Possible fuel sources include renewable biomass, natural gas, or coal syngas, and the cycle is a net producer of water when air cooled condensers are used.

From the turbines, the steam/CO_2 exhaust gas is cooled, separating into its components, water and CO_2, with the latter either sold or stored. The gas generator technology has been used successfully in aerospace applications for decades, including in the Space Shuttle Main Engines, where hydrogen and oxygen are combusted to produce pure steam at high temperature and pressure. Likewise, high-temperature, high-pressure turbines have been used successfully in aerospace applications.



The CES Process

Achievements of the company include:

<u>Technology Status</u>

- CES has 23 issued patents and more than 30 pending applications, domestic and foreign.

“Proof of Concept” Prototype

- In 2000 CES proved its concept with a 110 kW_t pilot project at the University of California, Davis, with co-funding provided by the California Energy Commission (CEC).

20 MW_t Gas Generator

- US DOE awarded CES a $2.5 million grant under the Vision 21 Program to design and build a 20 MW_t gas generator. CES has built and successfully tested in 2003 its 20 MW_t, unit, operating at pressures of up to 100 bar and temperatures between 300 ^oC and 1650 ^oC.

20 MW_t Demonstration Project – Kimberlina Power Plant

- The CEC awarded CES $4 million in funding to design and build a Demonstration Plant using CES technology, as part of a $12 million project. Major corporations Mirant and Air Liquide are participants, along with the US Department of Energy. In August 2003 CES acquired a 5 MW_e idle biomass plant, which has been repowered as a multi-fuel zero emission plant. Initial tests are being conducted with natural gas, with coal or biomass in subsequent phases. First synchronization to the grid occurred in February 2005, and more than 900 hours have been logged to date. Testing will continue through 2006.

DOE-supported Oxy-Fuel Rankine Cycle Systems Development

- In September 2005 the DOE signed two contracts with CES and Siemens Power Generation, Inc. to develop advanced turbines and combustors capable of operating on coal syngas. This program will enable 100% separation and capture of CO_2 and will achieve long-term power system efficiencies of 50% to 60%.

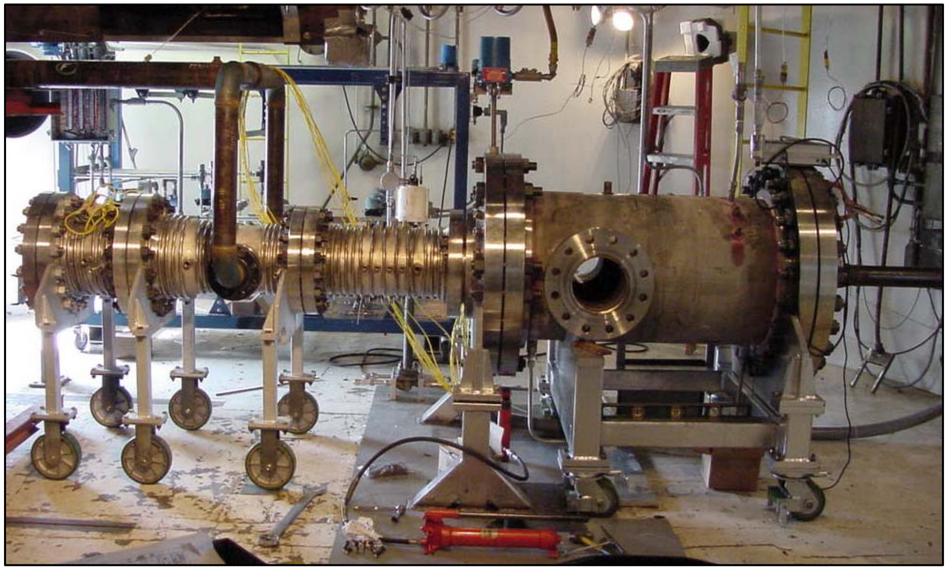
- CES will develop and demonstrate a new combustor technology powered by coal syngas and oxygen. The project team will evaluate and redesign the combustion sequence to achieve the ideal ratio of oxygen to fuel, a critical parameter in achieving optimum combustion and reducing costs. The DOE portion of this contract is $4.5 million, and the project duration is 39 months. The kickoff meeting was held in November 2005. Project participants include Siemens Power Generation, ConocoPhillips, Kinder Morgan, Air Products, and Air Liquide.

- Siemens Power Generation will combine current steam and gas turbine technologies to design an optimized turbine that uses oxygen with coal-derived hydrogen fuels in the combustion process. In this break-through project, system studies will show how this totally new turbine can be integrated into a highly efficient near-zero emission power plant. The DOE portion of this contract is $14.5 million, and the project duration is 56 months. The kickoff meeting was held in November 2005. CES is a project participant with Siemens Power Generation on this contract.

Commercial Applications

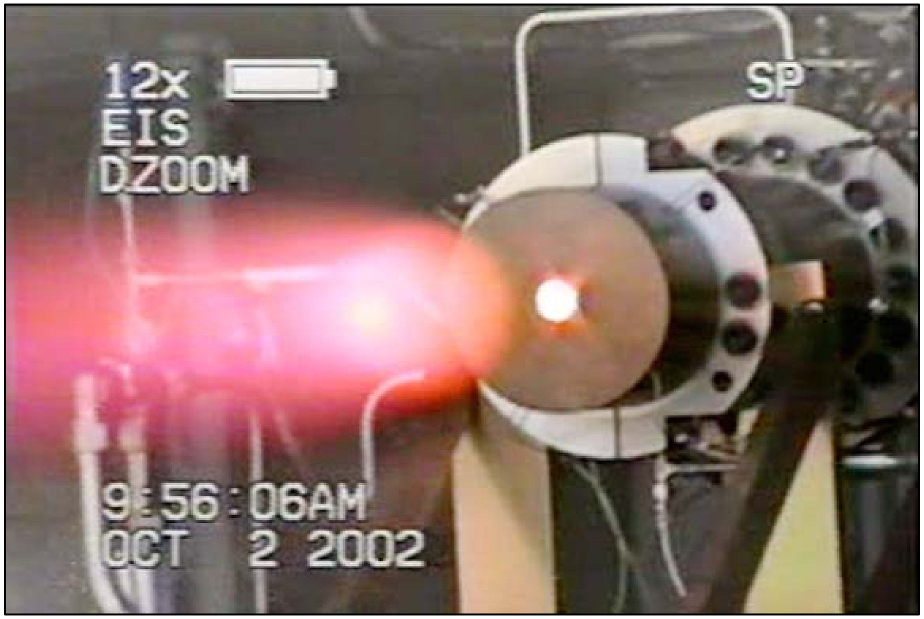
- Funded feasibility studies are currently underway for 50 MW zero-emission plants in Norway (see www.co2.no) and the Netherlands. Projects are also under development in the United States. Investment decisions on these “first generation” zero emission plants are expected in 2006.

CES 20 MW_t Gas Generator



Reheater for CES System (designed by DOE- NASA tested)

CES 20 MW_t Gas Generator – 100 bar & 850 ^oC



CES 20 MW_t Gas Generator – 100 bar & 1650 ^oC

20 MW_t Multi-Fuel Testing Facility – Bakersfield, California USA
(venting the Steam/CO_2 drive gas – oxygen plant to the left)

5.5 MW Steam Turbine (operating on a steam/CO2 drive gas) and Generator

Inaugural Workshop

International Oxy-Combustion Research Network

Vattenfall Europe Mining and Generation AG Head Office
Cottbus, Germany

29th and 30th November 2005

Poster Contribution

Oxyfuel Process for Hard Coal with CO_2 Capture – ADECOS Project First Results

by:

Prof. Alfons Kather

Hamburg University Of Technology
Institute Of Energy Systems
Denickestraße 15, 21073 Hamburg

This page is intentionally left blank

Oxyfuel Process for Hard Coal with CO_2 Capture

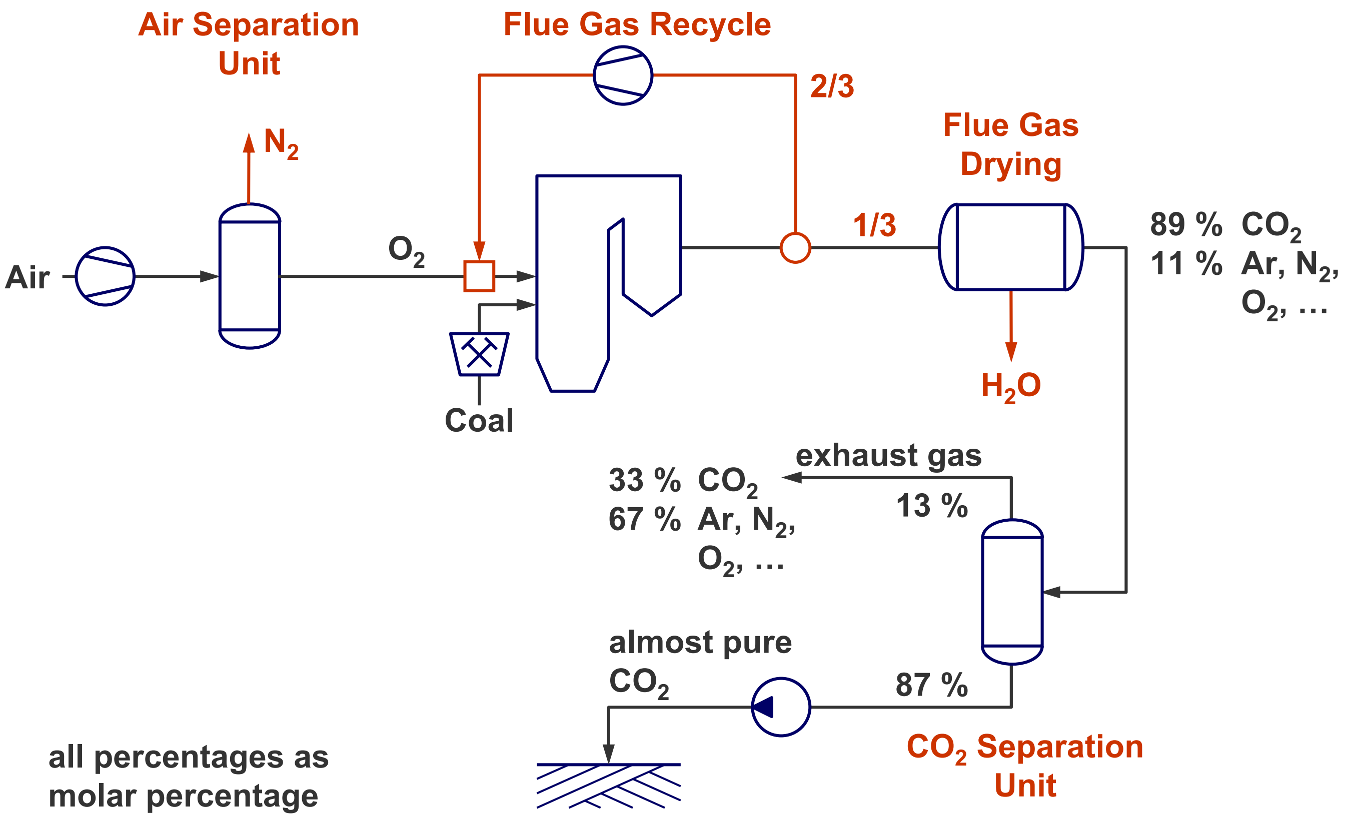
First Results

C. Hermsdorf
A. Kather
M. Klostermann
K. Mieske

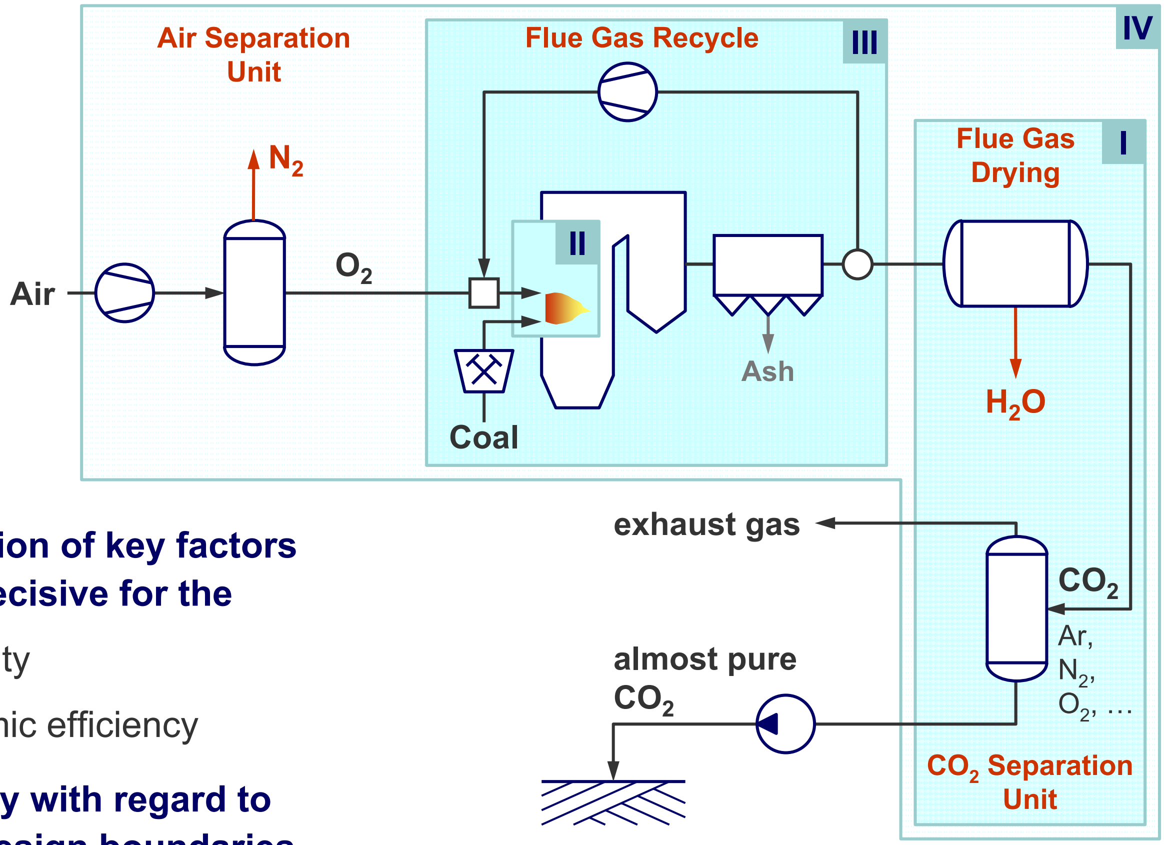
Hamburg University of Technology

TUHH
Technische Universität Hamburg-Harburg

Fourth Nordic Minisymposium on Carbon Dioxide Capture and Storage, Helsinki, September 8-9th, 2005



all percentages as molar percentage

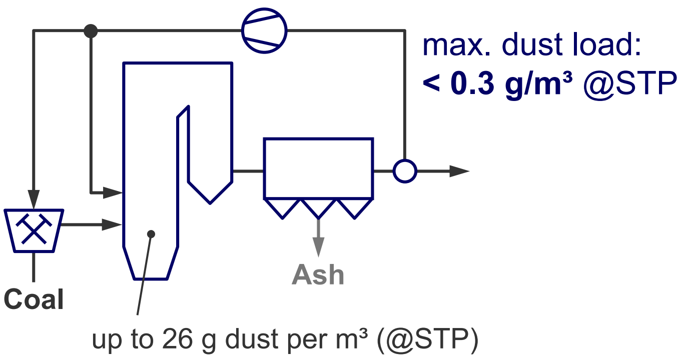


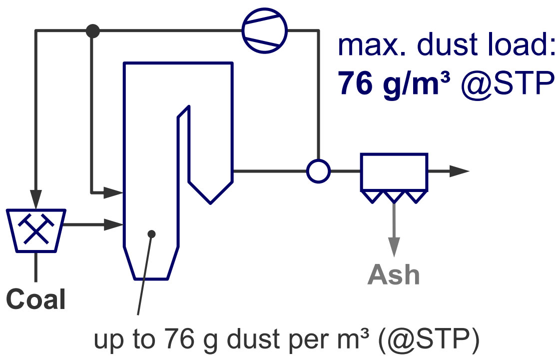
Objective

Identification of key factors that are decisive for the

- feasibility
- economic efficiency

particularly with regard to realistic design boundaries.



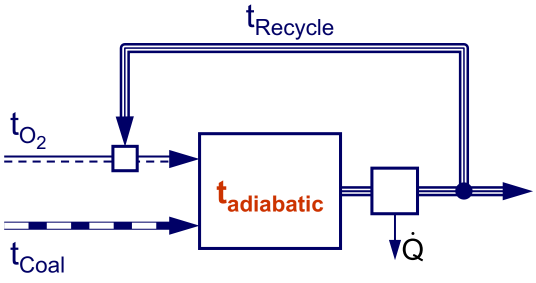


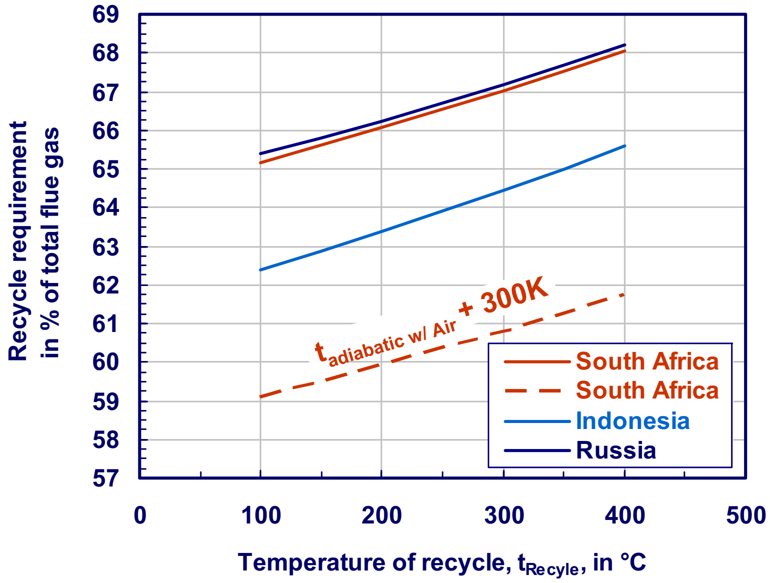
Low-dust recycle

- \+ enables high-efficiency **axial**-flow fan
- – temperature limited to **190 °C**, **270 °C** with blade cooling
  - ➡ mill internal coal drying usually at approx. 300 °C
- – large dust precipitator
- – long recycle ducts

High-dust recycle

- – requires low-efficiency **radial**-flow fan
- – increases wear
- \+ short recycle ducts
- \+ small dust precipitator
- \+ temperature **up to 350 °C** possible
  - ➡ mill internal coal drying





- **Condition:**

  $t_{adiabatic\ w/\ Air} = t_{adiabatic\ w/\ O_2+Recycle}$

- **Underlying assumptions:**

  t_{Air} = 320 °C

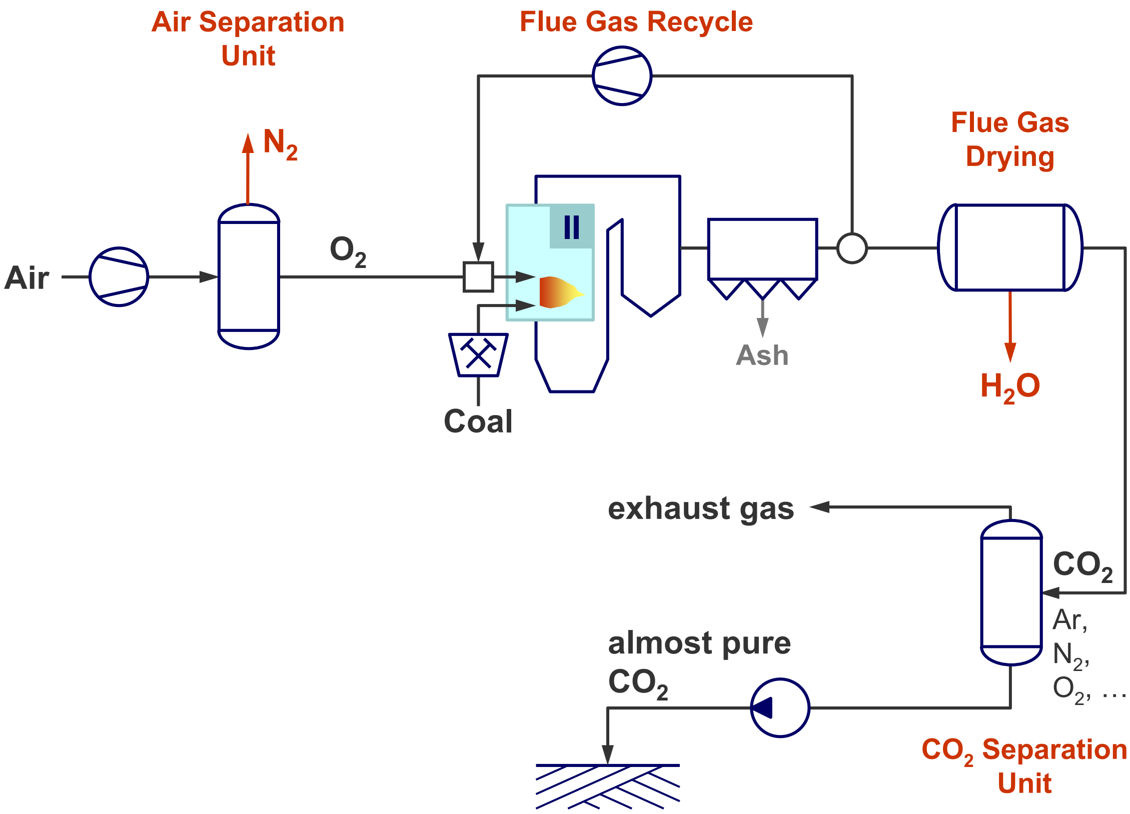
  t_{O_2} = 25 °C

  t_{Coal} = 40 °C

  O_2-excess: 15 %

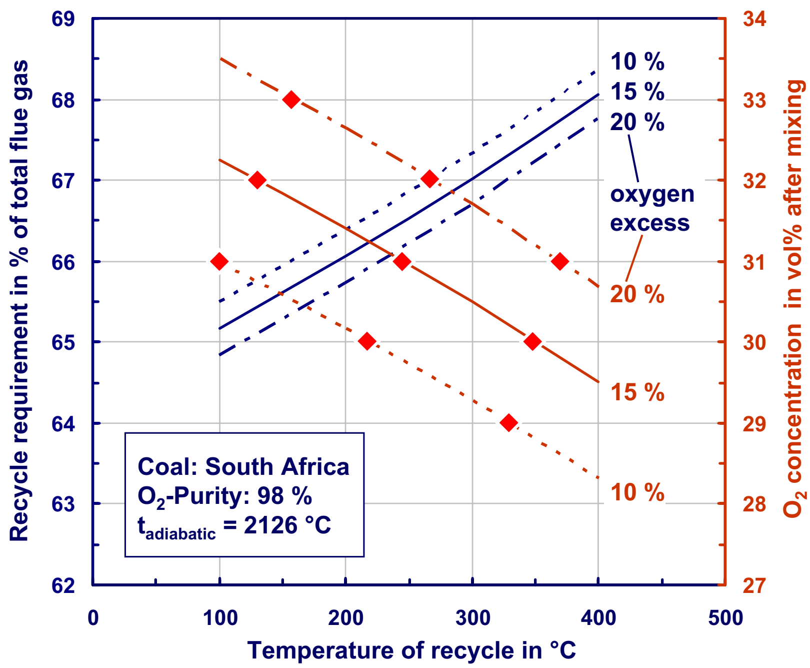
  O_2-purity: 98 %

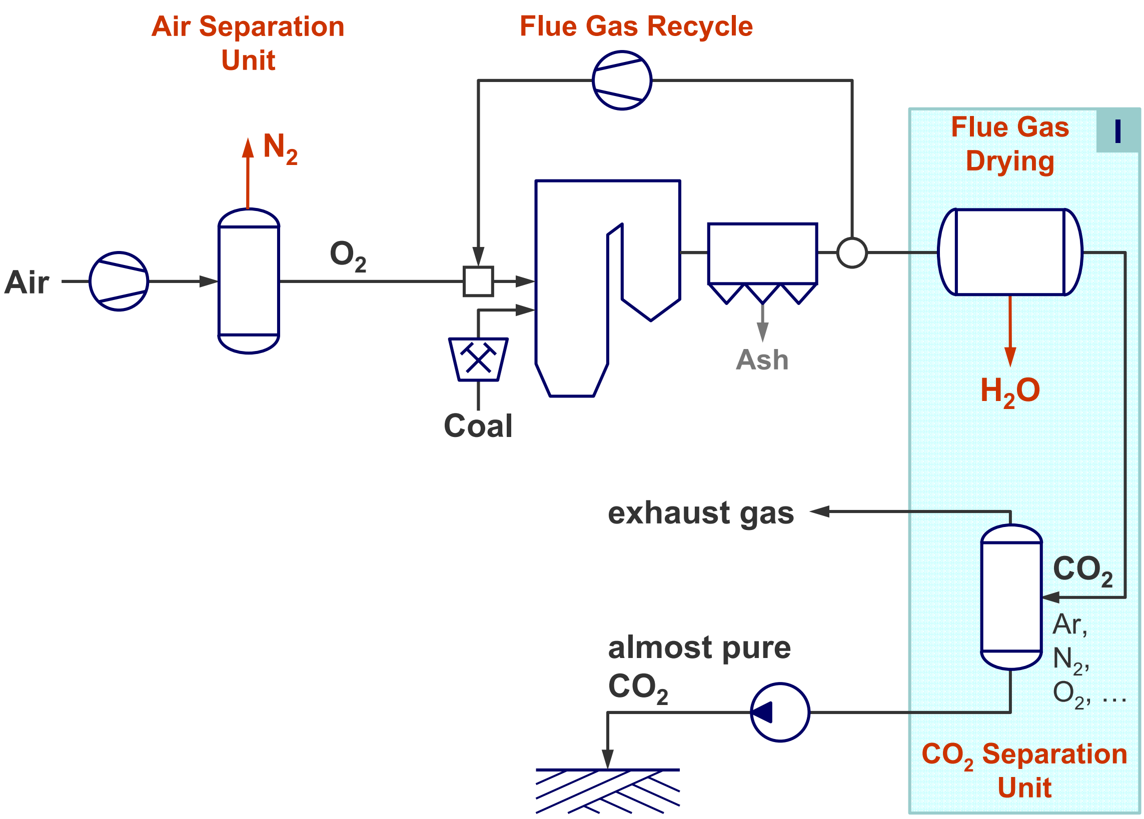
	Composition (in wt%)							NCV	$t_{ad,Air}$
Coal	C	H	O	S	N	Ash	H_2O	MJ/kg	°C
South Africa	65,93	3,63	7,25	0,61	1,58	13,60	7,40	25,40	2126
Indonesia	58,70	4,43	8,82	1,00	1,05	5,00	21,0	22,69	2008
Russia	70,09	3,70	7,37	0,30	1,23	9,81	7,50	27,20	2160



- **First Assumption:** Oxygen and recycled flue gas are mixed completely before combustion

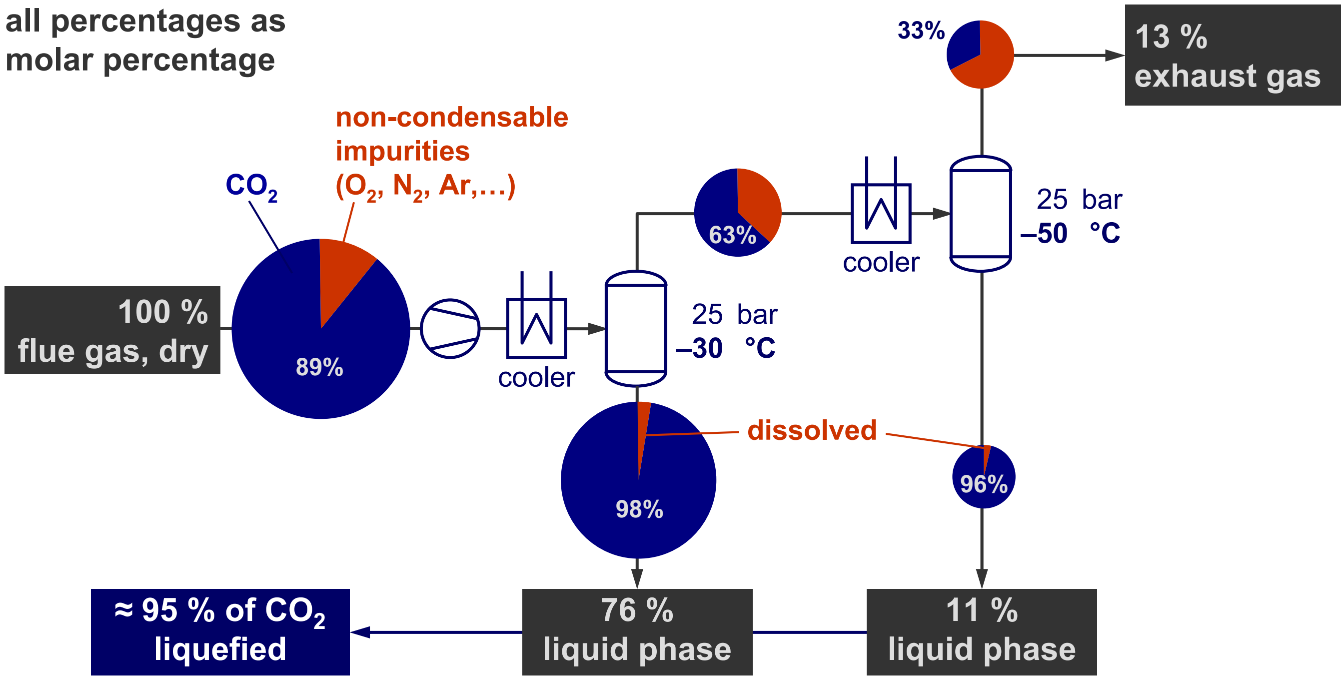
  Oxygen concentration
  - rises with reducing recycle,
  - is always above 21 vol%.
- **First combustion experiments (◆)**
- **Later experiments**
  - investigation of possible benefits using different oxygen concentrations at different phases of the combustion





Influence of Non-Condensables Impurities on the CO_2 Separation from dry Flue Gas (example)

TUHH Technische Universität Hamburg-Harburg



An 100 % CO_2 liquefaction is not possible in the presence of non-condensables!

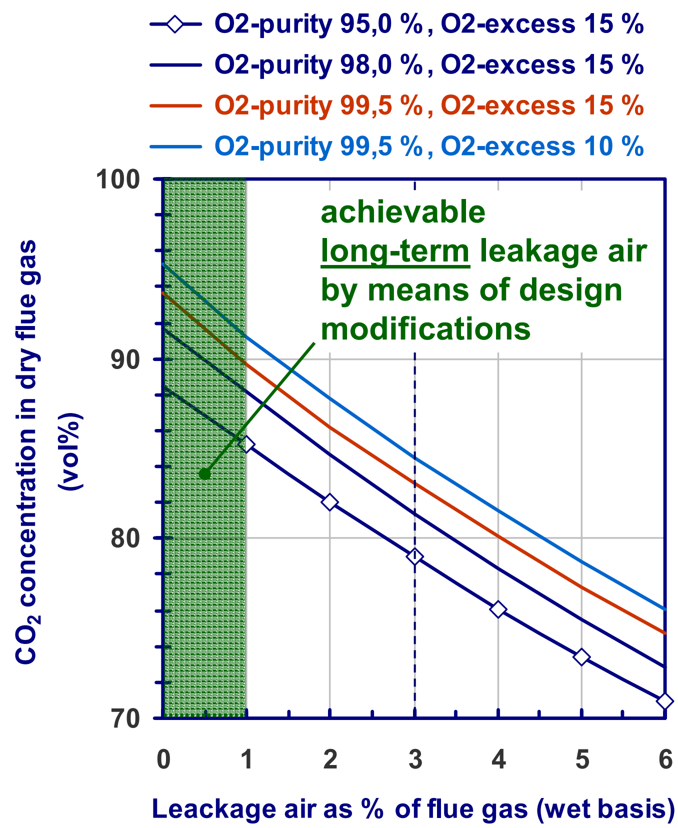
Note: exact numbers cannot be predicted until phase equilibrium data are available

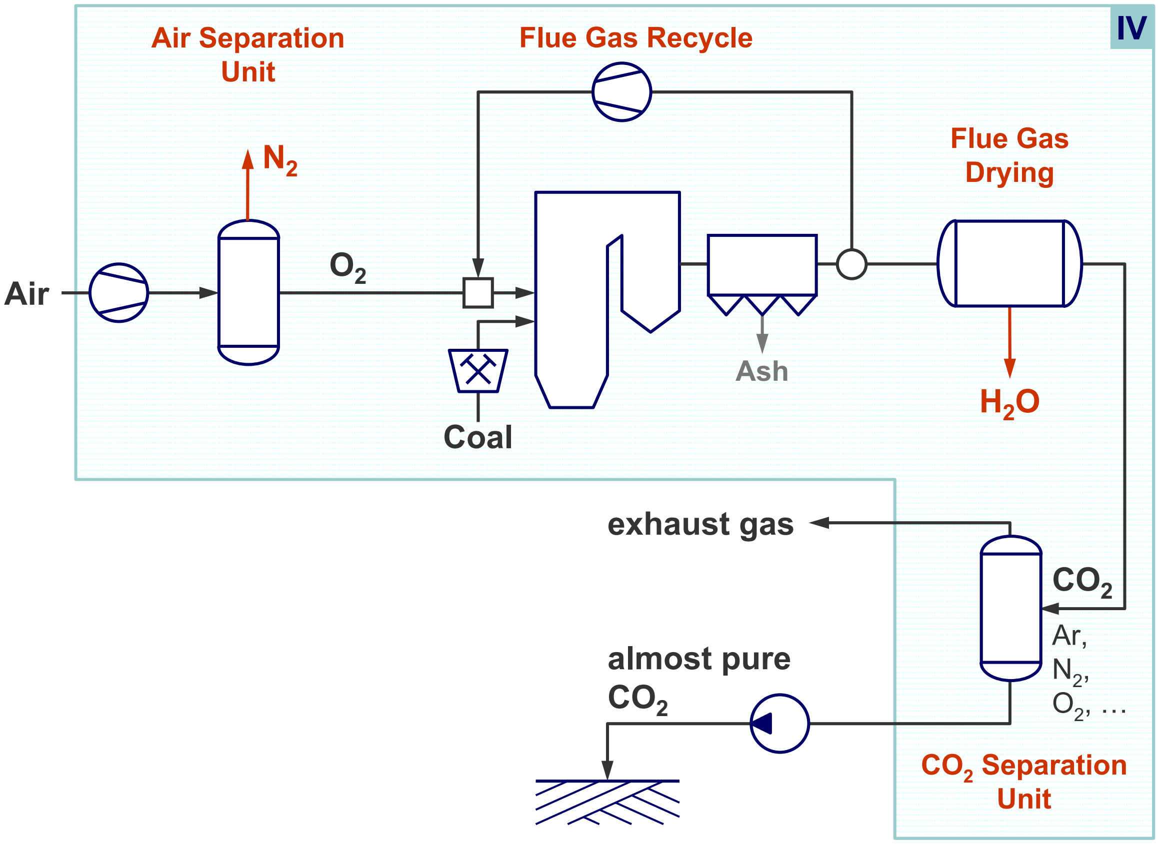
Sources of Non-Condensables and their Minimization Potential

TUHH Technische Universität Hamburg-Harburg

- **Sources of non-condensables**
  - fuel‘s nitrogen (and sulfur)
  - oxygen excess (➡ O_2 residue)
  - incomplete air separation (➡ Ar)
  - **leakage air**
- **Leakage Air**
  - approx. **3 %** of flue gas flow for a new conventional power plant
  - up to 10 % over the years for power plants in use

➡ **Leakage is <u>the</u> most influential source of non-condensables and could be radically minimized**





TUHH
Technische Universität Hamburg-Harburg

- **Underlying reference technology**
  - Reference power plant North-Rhine Westphalia: **η = 45,9 % (net)**
    power output: 556 MW (net), 600 MW (gross) η = 46,9 % (gross)
- **Key power consumers** (based on 600 MW gross power output)
  - **Air Separation Unit:**
    approx. 110 MW to attain 98 vol% oxygen purity
    70 MW at the expense of oxygen purity (95 %) using a new, not yet realized separation technology (3-column-process)
  - **CO_2 Separation Unit:**
    50 MW worst case
    < 30 MW possibly when using absorption refrigeration
- **Estimated efficiency loss:** **$\Delta\eta$ = 8…13 % (abs.)**