2^{nd} MEETING OF THE OXY-FUEL NETWORK

Report Number: 2007/16

Date: November 2007

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-Fuel is organised by IEA Greenhouse Gas R&D Programme. The organisers acknowledge the financial support provided by Alstom for this meeting and the hospitality provided by the hosts Alstom.

The report should be cited in literature as follows:

IEA Greenhouse Gas R&D Programme (IEA GHG), "2nd Meeting of the Oxy-Fuel Network, 2007/16, November 2007".

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
www.ieagreen.org.uk.
www.co2captureandstorage.info

2nd WORKSHOP

IEAGHG INTERNATIONAL OXY-COMBUSTION RESEARCH NETWORK

Hilton Garden Inn
Windsor, CT, USA

25th and 26th January 2007

EXECUTIVE SUMMARY

The 2nd IEA Greenhouse Gas R&D Programme International Oxy-Combustion Workshop was held at Windsor, CT, USA on the 25th and 26th of January 2007 and was hosted by Alstom Power Inc. The workshop brought together 88 participants from industry, research institutes and universities covering 16 countries worldwide. The presentations and discussions at the workshop covered a wide range of topics looking at on-going studies and experimental results, modelling studies, new developments in oxygen production and CO_2 processing, and identification of various issues relevant to the demonstration of oxy-combustion technology.

Regarding the future direction and the different issues involving the development of oxy-combustion technology for power generation with CO_2 capture the workshop concluded that this will have three strands namely:

- In the short term, development would concentrate on enabling technologies that would be suitable for retrofit of existing plant or new build. This technology would be totally based on current conventional power plant designs but would be equipped with new high efficiency and air-tight boilers. This type of boiler would also allow operation of the boiler in air firing mode. (i.e. Projects developed by Vattenfall, CS Energy/IHI and TOTAL)
- In the intermediate term, development would look at the enabling technologies that would build the next generation power plant purposely for oxy-combustion. It could be perceived that this type of boiler would be similar to the current conventional boiler but never planned for air firing. (i.e. CANMET development in HYDROXY Burner)
- In the longer term, development of oxy-combustion technology would look at new technologies that would be totally different from current conventional boilers (i.e. Chemical Looping Combustion, Praxair's OTM membrane, CES technology).

The workshop also highlighted that there are two main development issues common to any type of oxy-combustion technology which are; the need to address the energy penalty related to the oxygen production and the need to address the requirements for the CO_2 quality. As far as the development of the oxygen production is considered there are two routes forward:

- The near term development would look at the improvement of current cryogenic distillation processes. In this case the questions to answer include: what could be the optimum oxygen purity in terms of minimising the CAPEX and the OPEX?, what is the potential for integration with the boiler island and the CO_2 processing unit?, and what could be the permissible maximum capacity of current ASU cryogenic technology? (e.g. could we have a single train ASU > 5000 TPD?)

- In the medium to long term focus would be on the development of various breakthrough technologies such as: membrane technologies (i.e. ITM, OTM, CARS) and/or chemical looping combustion processes (no oxygen production required)

The workshop stressed the need to discuss the issue on CO_2 purity. Particular questions that needed to be addressed include:

- What are the requirements of the CO_2 storage site with regard to the major impurities (i.e. O_2, N_2 and Ar)?
- What are the different technical issues involving the removal of minor impurities (i.e. SOx, NOx, Hg and other trace metals)?

For the short term development of oxy-combustion process, the following points should be noted:

- Validated simulation of the oxy-combustion process will be the key to allow existing plants to be retrofitted with confidence. There is a need to develop simulation tools that would allow modelling of heat transfer, ignition, devolatililisation and char burnout kinetics, and ash partition and deposition.
- There is already a good understanding in NOx and SO_2 formation (including sulphation of the ash). However, there is still a need to obtain more data for SO_3, Hg and trace metal emissions.
- The compression and condensation process proposed by Air Products is considered one of the most elegant solutions for CO_2 processing. However, the reaction mechanisms and capture efficiency of these minor impurities should be verified.

INTERNATIONAL OXY-COMBUSTION NETWORK FOR CO_2 CAPTURE
Report on 2nd Workshop

Hilton Garden Inn
Windsor, CT, USA

25th – 26th January 2007

1. INTRODUCTION

This report highlights the key points of all the presentations of the 2nd workshop of the International Oxy-Combustion Network for CO_2 Capture that was organised by the IEA Greenhouse Gas R&D Programme (IEA GHG) and was hosted by Alstom Power Inc.. The workshop was held at the Hilton Garden Inn, Windsor, CT, USA on the 25th and 26th of January 2007. A visit to the Alstom's Power Plant Laboratories was arranged in the afternoon of the 24th of January.

IEA GHG would like to acknowledge and thank Dr. John Marion and Dr. Woody Fiveland for their full support to this workshop.

2. WORKSHOP OVERVIEW

The least developed among the three leading CO_2 capture technology options for the power generation industry is oxy-combustion. In recognition, of the different efforts by industry, academia and research institutes to develop and demonstrate the techno-economic feasibility of oxy-combustion technology as a CO_2 capture option for power plant application in the near future; the IEA Greenhouse Gas R&D Programme 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 to discuss various issues relevant to the development of the technology.

The inaugural workshop was hosted by Vattenfall AB and was held at Cottbus, Germany on the 29th and 30th of November 2005 and a visit to the Schwarze Pumpe Power Plant, the future site of the first complete oxy-coal combustion pilot plant with CO_2 capture demonstration, was part of the meeting. To follow up the discussion undertaken during the 1st workshop, IEAGHG in co-operation with Alstom Power Inc. organised the 2nd Workshop which was held in Windsor, CT, USA. The 2nd workshop started with a facility visit to Alstom's Power Plant Laboratories. This included a visit to their $25MW_{th}$ boiler simulator, $3MW_{th}$ Oxy-CFB test rig, chemical looping combustion test rig, and their analytical and material testing laboratory. The opening session of the meeting started with two keynote presentations by Prof. Adel Sarofim of Utah University and Dr. Woody Fiveland of Alstom. This was followed by 19 other excellent presentations over the two day meeting which presented a wide range of topics looking at the experimental results, on-going studies, new developments and discussion on various issues regarding the oxy-combustion technology for power plant application.

The first day of the meeting ended with a discussion forum led by Prof. Janos Beer of MIT; wherein the discussion highlighted the various key issues related to power plant efficiency, operational issues and flue gas processing.

Finally, the main highlight of the workshop that concluded the meeting was the panel discussion where the six on-going large scale oxy-combustion demonstration projects worldwide presented any updates to their projects.

The agenda of the workshop is presented and described in the succeeding section.

3. PROGRAMME / AGENDA

The agenda is presented overleaf. Over the 2 days, the workshop covered the following topics:

- Experimental and Modelling Studies – A Review of Oxy-Fuel Combustion R&D Activities.
- Work-in- Progress, Development in Oxy-Fuel Combustion Studies.
- Oxygen Production, Membrane Technology and CO_2 Processing – Overview to the Different R&D Activities for Power Generation Industry.
- Advance oxy-combustion concepts (Chemical Looping Combustion)
- An Overview, Progress and Development in Large Scale Oxy-Fuel Combustion Project

The workshop featured an update to the progress in the development of large scale oxy-coal combustion pilot plant studies currently on-going in Europe, Australia and USA.

2nd Workshop

IEAGHG International Oxy-Combustion Network

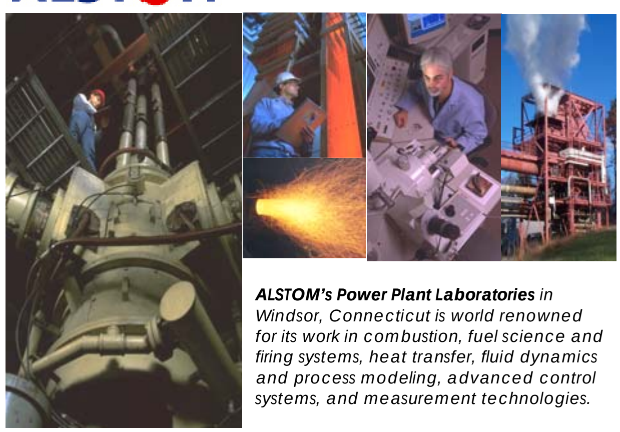
Hilton Garden Inn
Windsor, CT, USA

25th and 26th January 2007

24th January 2007 – Facility Visit (Please register for this activity)

	Visit to Alstom's 3MW Oxy-CFB and CLC test rig.	
1500 – 1745	**Meeting Point:** **Time:**	**Hotel Reception** **1445**
	Welcome Drink Reception at Alstom Facility	

ALSTOM



***ALSTOM's Power Plant Laboratories** in Windsor, Connecticut is world renowned for its work in combustion, fuel science and firing systems, heat transfer, fluid dynamics and process modeling, advanced control systems, and measurement technologies.*

1800 - 1900	**Pre-Registration (Hilton Garden Inn Reception)**

25th January 2007 – AGENDA (Day 1)

0730 – 0830	Continental Breakfast
0830 – 0900	**Welcome Address – ALSTOM Power Inc.** John L. Marion, VP Global Technology – Boiler Business, USA **IEA Greenhouse Gas R&D Programme: Background to International Oxy-Combustion Network** John Topper, Managing Director, IEA Greenhouse Gas R&D Programme (IEA EPL)., UK
	SESSION 1: Keynote Presentations *Chairperson: John Topper, IEA Greenhouse Gas R&D Programme, UK*
0900 – 0940	**Overview of Oxy-Fuel Combustion Technology: Progress and Remaining Issues** Prof. Adel Sarofim, University of Utah, USA
0940 – 1020	**An Overview to Alstom's R&D Activities on Oxy-Combustion Technology Application for Power Generation Industry** Woody Fiveland, Alstom Power Inc., USA
1020 – 1040	Coffee Break

	SESSION 2a: Oxy-Combustion Experimental Study and Modelling *Chairperson: Prof. Klaus Hein, University of Stuttgart, Germany*	
1040 – 1100	**Combustion Tests & Modelling of the Oxy-fuel Process – An Overview of Research Activities at Chalmers University** Klas Andersson, Chalmers University, Sweden	
1100 – 1120	**Stability of Axial Pulverised Coal Flame Under Oxy-Combustion Conditions** Prof. Jost Wendt, Reaction Engineering / University of Utah, USA	
1120 – 1140	**Pilot Scale Experiments Giving Direct Comparison Between Air and Oxy-Firing of Coals and Implication for Large Scale Plant Design** Toshihiko Yamada, IHI, Japan	
1140 - 1200	**Coal Particle Ignition, Devolatilisation and Char Combustion Kinetics During Oxy-Combustion** Christopher Shaddix, Sandia National Laboratory, USA	
1200 - 1220	**CFD Modelling for Oxy-Combustion Processes** Karin Eriksson, Vattenfall R&D, Sweden	
1220 – 1340	Lunch	
	SESSION 2b: Oxy-Combustion Experimental Study and Modelling *Chairperson: Klas Andersson, Chalmers University, Sweden*	
1340 - 1400	**Ignition of Oxy-Fuel Flames** Prof. Terry Wall, Newcastle University, Australia	
1400 - 1420	**Thermoacoustic Instabilities in a CO_2 Diluted Oxy-Fuel Combustor** Mario Ditaranto, SINTEF Energy Research, Norway	
1420 - 1450	**Experimental Investigation of Oxy-Coal Combustion at IVD Using 20 and 500 kW PF Test Facilities** Joerg Maier, IVD – University of Stuttgart, Germany	
1450 - 1510	**Modelling, Design and Pilot-Scale Experiments of CANMET's Advanced Oxy-Steam Burner** Carlos Salvador, CANMET, Canda	
1510 - 1530	Coffee Break	
	SESSION 3: CO_2 Processing, Oxygen Production and Membrane Technology *Chairperson: Nicholas Perrin, Air Liquide, France*	
1530 – 1550	**Purification of CO_2 from Oxyfuel Combustion** Vince White, Air Products, UK	
1550 – 1610	**Oxy-Fuel Combustion Using OTM for CO_2 Capture from Power Plants** Minish Shah, Praxair, USA	
1610 – 1630	**ITM Oxygen : Progress Toward Reduced CO_2 Capture Cost** Kevin Fogash, Air Products, USA	

	SESSION 4 : OPEN FORUM *Chairpersons: Prof. Janos Beer, MIT, USA*

1630 - 1730 **THE REMAINING ISSUES FOR OXY-COMBUSTION TECHNOLOGY**

- Summary to Day 1 Presentations
- Discussion on various issues relevant to development oxy-combustion technology
    - boiler and burner development
    - oxygen production
    - CO_2 processing
    - Process integration

1900 Workshop Dinner (Sponsored by Alstom Power Inc.)

26th January 2007 – AGENDA (Day 2)

0730 – 0820 Continental Breakfast

0820 – 0830 **Session Opening – Administrative Announcement**

SESSION 5: On-Going Oxy-Combustion Studies
Chairperson: Prof. Jost Wendt, University of Utah / Reaction Engineering, USA

0830 – 0850 **Development of Cost Effective Oxy-Combustion for Coal Fired Boilers**
Hamid Farzan, Babcock & Wilcox, USA

0850 – 0910 **Doosan Babcock Oxy-Fuel Development Plans**
Ragi Panesar, Doosan Babcock Energy Ltd., UK

0910 – 0930 **State of Development of Oxy-Coal Combustion Research Initiative by Fundacion Ciudad de la Energia in Spain**
Prof. Vicente Cortes Galeano, University of Seville, Spain

0930 – 0950 **Oxy-Fuel Process for Hard Coal with CO_2 Capture – A Part of the ADECOS Project**
Prof. Alfons Kather, Technical University of Hamburg-Harburg, Germany

0950 - 1010 **Mini-Discussion Session**

1010 – 1030 Coffee Break

SESSION 6: Advance Oxy-Combustion Concept
Chairperson: Greg Liljadahl , Alstom Power, USA

1030 - 1050 **Development in Chemical Looping Combustion**
Tobias Mattisson, Chalmers University, Sweden

1050 - 1110 **Fixed Bed Membrane Assisted CLC**
Sander Noorman, University of Twente, The Netherlands

1110 - 1130 **CLC R&D Efforts of Alstom**
Herb Andrus, Alstom Power Inc., USA

1130 - 1245 Lunch

SESSION 7: Panel Discussion – Large Scale Oxy-Combustion Demonstration Project *Chairperson: Sho Kobayashi, Praxair, USA*	
1245 – 1525	**Coal-Based Oxy-Fuel System Evaluation and Combustor Development** Leonard Devanna, Clean Energy System, USA
	Oxy-Combustion and CO2 Storage Pilot Plant Project at Lacq Nicolas Aimnard, Total, France
	The Saskatchewan Advantage: SaskPower Clean Coal Project Update Bob Stobbs, SaskPower, Canada
	Callide-A Oxy-Fuel Project Status Chris Spero, CS Energy, Australia
	CO_2 Free Power Plant Project: Status Oxy-Fuel Pilot Plant Lars Strömberg, Vattenfall AB, Sweden
	Moving Oxy-Combustion Forward:- Overview of Jupiter Oxygen's R&D Activities Brian Patrick, Jupiter Oxygen, USA
1525 - 1530	**Closing Session** Wrapping Up and Future Activities

4. WORKSHOP ATTENDEES

The workshop brought together 88 participants from the power generation industries, boiler and combustion equipment manufacturers, oxygen production and CO_2 processing industries, research institutes and universities covering 16 countries worldwide. The attendance list is given in Appendix 1.

Figure 1: Participants of the 2nd International Workshop held at Windsor, CT, USA (24th January 2007)

Excluding participants from Alstom Power, breakdown of participants shows that there are:

- 33 participants from N America (44.6%);
- 33 from Europe (44.6%);
- 4 from Australia (5.4%);
- 2 from Japan (2.7%); and
- 2 from South Korea (2.7%)

5. PRESENTATION HIGHLIGHTS

5.1. WELCOME ADDRESS – ALSTOM POWER INC.

John Marion, VP Global Technology – Boiler Business, Alstom, USA

John Marion, Vice President of the Global Boiler Business Technology of Alstom, welcomed the participants of this workshop held in the meeting room of Hilton Garden Inn, CT.

His welcome address presented an equipment manufacturer's opinion on reduction of greenhouse gas emissions from power generation industry:

- It was stressed that Alstom's belief in providing a diverse mix of technologies for power generation is a critical element in providing affordable, reliable, and environmentally sound energy.
- Alstom has been active in developing technology for CO_2 reduction for power plant applications.
- It could be noted that improving efficiency in the power plant is a no regret strategy that can be implemented today. It was mentioned that efficiency improvement is a key element to the viability of CO_2 capture and storage technology.
- Although Alstom has been active in developing several carbon capture technologies, this presentation clearly explained why Alstom decided to pursue the development of oxy-combustion. It was particularly pointed out that oxy-combustion technology is complimentary to current development in the boiler/steam power plant and environmental control.

The presentation concluded by stressing the following:

- It is essential to design new coal fired power plants with highest possible efficiency to minimize CO_2 and other emissions.
- It was indicated that there is no single technology answer in mitigation of CO_2 emission of power plants.
- It was clearly noted that cost attractive options are needed and should be actively supported, especially in:
    - developing technology that could provide a significant Breakthrough specifically in cost terms (i.e.: chemical looping and advanced oxygen production)
    - highlighting the importance of developing technologies that could be Retrofitable (i.e.: oxy-firing and ammonia scrubbing)

5.2. Oxy-Fuel Combustion: Progress and Remaining Issues

Prof. Adel Sarofim, University of Utah, USA

The first keynote presentation for the 2nd workshop was presented by Prof. Adel Sarofim of University of Utah. An important aspect for this workshop was to provide a clear understanding of the progress in the development of oxy-combustion and identify the different technical issues that should be dealt with in preparation for the demonstration and deployment of this technology.

The keynote address by Prof. Adel Sarofim explained the current understanding of the principles of this combustion technology. The keynote speech clearly identified the gaps in knowledge, and presented the different issues in the development of oxy-combustion. Specifically, this presentation discussed the following points:

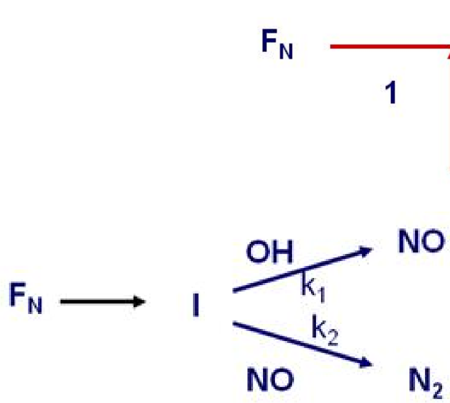
- Basic principles of oxy-combustion looking at the aspects of heat transfer, emissions and combustion considerations.
- Different technical considerations for external recirculation of flue gas for greenfield and retrofit application.

- Different technical considerations for internal recirculation of flue gas for new plant design (therefore considering the reduction of cost).
- The issues involving the cost of oxygen production and development in new oxygen production techniques.

The review presented the current understanding of oxy-coal combustion relevant to the impact of the amount of flue gas recycled to the heat transfer of the boiler. The following points were summarised:

- The recycle ratio R (as defined by Praxair as the molar ratio of recirculated flue gas to oxygen supplied) is determined as the value required to match the heat transfer for the air-fired furnace (not adiabatic flame temperature).
- To match the heat flux of the air fired combustion, R is predicted to be in the order of 3. This value increases with increasing gas emissivity (size of furnace), oxygen purity, coal type, and temperature of the recycled flue gas; and this could be reduced by solid recycle (in case of fluidized bed combustion).
- The mean velocity of gases is reduced by the factor of ≈ 0.84. This will provide a longer residence time in the radiant section of the furnace.
- The effect of lower velocity in the convective section is more than offset by lower kinematic viscosity for the oxy-combustion, so the Reynolds numbers and convective heat transfer coefficients will increase. The balance of heat transfer between the water cooled walls, radiant and reheat panels, and convection section will differ slightly between air and oxy-combustion but can be compensated for by either
    - Changes in the operation for plant retrofits or
    - Changes in the design for new units.
- The developments of zone models or CFD models are important tools for designing oxy-combustion boilers. However, predictive capability is constrained by the uncertainty in the thermal resistance of the ash deposits.

With regard to NO_x emissions, Prof. Sarofim noted that the mechanisms presented by Prof. Ken Okazaki (as shown in Figure 2) clearly explain consistent reduction of NOx due to (1.) reburn mechanism caused by recirculation of the NO_x component in the flue gas and (2.) decrease of fuel nitrogen conversion due to increased NO concentration in the combustion zone.



$$\alpha = \frac{k_1 (I)(OH)}{k_1 (I)(OH) + k_2 (I)(NO)} = \frac{1}{1 + \frac{k_2 (NO)}{k_1 (OH)}}$$

Figure 2: NOx formation and destruction mechanism under oxy-combustion conditions as proposed by Prof. K. Okazaki

where:

- $(R+1)(NO)_e = \alpha F_N + R(NO)_e(1 - \eta)$
- $(NO)_e = \alpha F_N / \{R\eta + 1\}$
- where α is fraction of fuel nitrogen converted to NO and η is fraction of NO destroyed by reburning

With regard to SO_2 emissions, the following points were noted:

- It was noted that sulphur removal with ash is increased up to 30% from the experimental trials of Babcock & Wilcox and IHI. Prof. Okazaki explained that an increase in the sulfation of the ash was caused by higher concentration of SO_2.
- An additional factor to be considered is the direct reaction of sulphur with $CaCO_3$.

Considering the issues with regard to the operation of the boilers under the oxy-combustion with recycled flue gas conditions, the following points were summarised:

- It was noted that it is essential to understand the impact to the flammability limit, flame stability, char and soot burn out by the CO_2 enriched flue gas as comburrent, and by the level of oxygen near the burner throat.
- It was clearly indicated there is a requirement to address the issues of design scale up, turn down operation, development of design tools, and operational safety.

The importance of quality of CO_2 toward the operation and design of the oxy-combustion capture plant was clearly stressed. It was indicated that the primary concerns will be in the constraint of the composition of the CO_2 to the processing plant and transport system.

The discussion with regard to the issue of CO_2 quality was reinforced by explaining the process suggested by Air Products in purification of the CO_2. It was clearly explained the impact of the non-condensable gases and the sources of these gases (from air ingress, excess O_2 in the oxidant and non-condensable from the ASU) in relation to what extent the CO_2 rich flue gas could be purified.

The background of the development oxy-combustion with external flue gas recirculation was briefly discussed. It was noted that the current commitment toward its development could largely contribute toward the commercialisation of the technology.

The development oxy-combustion with internal flue gas recirculation was introduced by presenting the use of aspirating burners (normally found in some glass and metal reheating furnaces) as example. It was noted that the potential of such application in future boiler design.

The cost of producing oxygen is one of the main concerns toward the development of oxy-combustion technology. On this issue the following were noted:

- The current ASU producing 95% pure oxygen would require 200 kWh/tonnes of O_2.
- It was noted that there are huge potential energy saving in various innovative design, for example:
    - Chemical looping technology
    - Membrane technology
    - CO_2 in-furnace capture technology

Finally, the presentation concluded by stating:

- that on-going pilot plant and laboratory scale studies showed the feasibility of the near term implementation of oxy-combustion technology for CO_2 mitigation;
- that oxy-combustion technology will be advantageous over IGCC due to better reliability, availability and familiarity; and
- that the long term prospect in the development of oxy-combustion technology would require the reduction of cost through technology breakthrough and innovation.

5.3. An Overview to Alstom's R&D Activities on Oxy-Combustion Technology - Application for Power Generation Industry

Woody Fiveland, Alstom Power Inc.

The second keynote presentation was given by Dr. Woody Fiveland of Alstom and the following were presented:

- An overview of the current technology available for conventional oxy-firing of coal.
- An overview of the advanced oxy-combustion concepts.
- Economic analyses of recent studies.
- Current test programme being undertaken by Alstom.

The motivations of Alstom in developing oxy-combustion were clearly defined presenting their near and long term strategy in the development of oxy-combustion technology for power generation application as:

- Most near-term solution: The use of commercially available air fired PC/CFB technology and enabling technologies
    - O_2 production by commercial cryogenic air separation
    - CO_2 capture, compression, and liquefaction
- Long term solution: Would require intermediate step leading to the more advanced processes, for example:
    - Oxygen Fired PC/CFB with Oxygen Transport Membrane
    - Chemical Looping Combustion
    - Chemical Looping Gasification

It was noted that economic analysis looking at the near term solution for oxy-coal combustion could be viable for commercial application of EOR considering:

- Electricity for sale
- CO_2 sale for oil field stimulation
- N_2 sale for oil field pressurization

The different options for oxy-firing technology were presented and compared to a conventional air fired case.

- For the oxy-PC case using flue gas recirculation to moderate combustion temperature and maintain 30% oxygen in the comburrent, the volume of the flue gas produced is about 65% of the flue gas volume of the conventional air fired case.
- For oxy-CFB case, the flue gas recirculation is much reduced due to the effect of solid recirculation. Oxygen in the comburrent is maintained at 70%, and the flue gas volume produced is about 28% of the flue gas volume of the conventional air fired case.

- Engineering study for a CFB based power plant producing 210MW$_e$ gross indicated that the oxy-CFB case when compared to conventional air fired CFB case would have:
    - 51% less plant area
    - 56% less volume
    - 65% less weight
    - 68% less cost

The most important aspect in potential cost saving for the oxy-combustion technology is the development of advanced oxygen production process. Cases for membrane technology and ceramic autothermal recovery for oxygen production were presented as examples.

Various economic studies were presented (See Figure 3). Alstom noted the following results indicating that oxy-combustion technology could be economically competitive as compared to other CCS options (based on levelized cost of electricity):

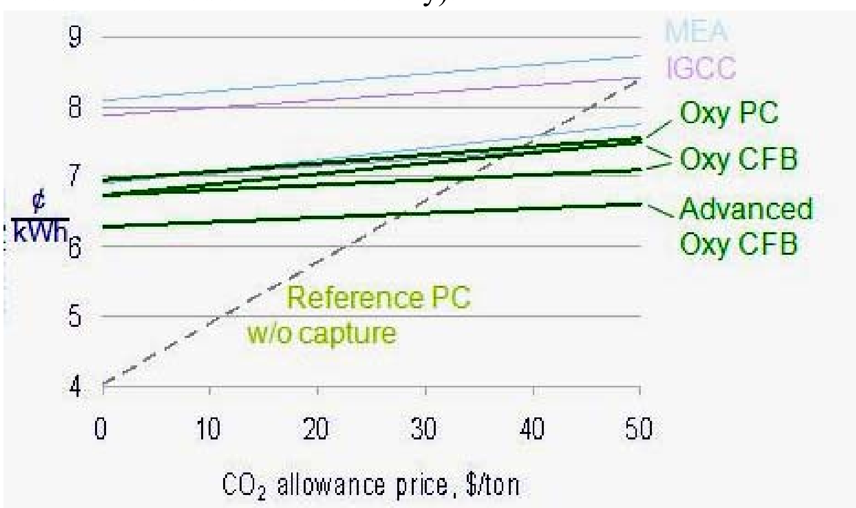


Figure 3: Economic analysis of oxy-coal combustion technology with considerations for EOR application

For an oxy-CFB case (producing 210 MW$_e$ gross) with CO_2 capture for EOR application, Alstom economic studies indicated that the plant could achieve break even in terms of the COE if:

- CO_2 is given a credit of $17 / tonne and N_2 is given a credit of $4 / tonne (2003 study) or
- CO_2 is given a credit of $28 / tonne (2003 study)

Various test programmes in Europe and N. America for oxy-PC combustion development participated by Alstom were presented. Some of these test programmes include:

- 100 kW$_{th}$ oxy-combustion test with Chalmers University under the ENCAP[1] project
- 500 kW$_{th}$ oxy-combustion test with IVD-University of Stuttgart (under the ENCAP project) and Technical University of Cottbus (under the ADECOS[2] project)
- 30MW$_{th}$ Vattenfall Pilot Plant study

[1] ENCAP Project – EU FP6 Project - "Enhanced Capture CO2 from Power Plant"
[2] ADECOS Project – "Advanced Development of the Coal-fired Oxyfuel Process with CO2 Separation" – under the COORETEC Programme of Germany

Figure 4 shows the conceptual design of the $30MW_{th}$ furnace and boiler to be supplied to Vattenfall Schwarze Pumpe Oxy-Combustion Pilot Plant Project:

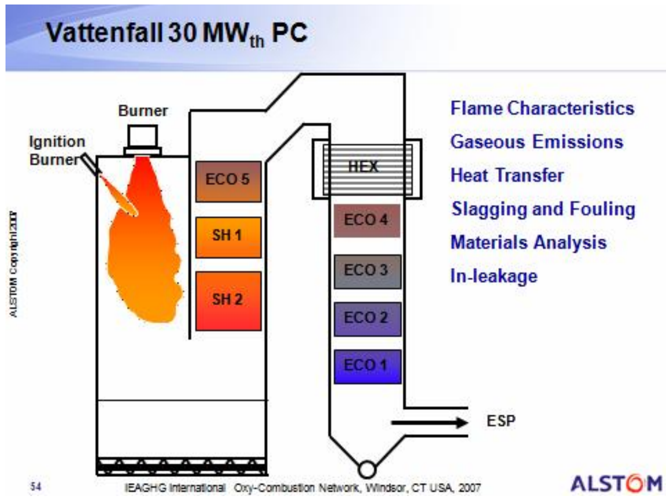


Figure 4: Schematics of the Vattenfall 30MWth Pilot PC Boiler

The importance of using Computational Fluid Dynamics (CFD) modelling was clearly mentioned as an essential design tool. The limitation of these tools in predicting char burnout and NOx emissions was also mentioned.

Finally, the presentation was concluded with the following statements:

- Oxy-firing for CO_2 capture in power generation application is a relatively near term cost competitive approach built on current technology
- On-going trials in various R&D activities for the development of oxy-PC or oxy-CFB present no show stoppers.
- Future development of oxy-combustion will be focused toward large scale oxy-PC / oxy CFB technology.

5.4. Combustion Tests & Modelling of the Oxy-fuel Process – An Overview of Research Activities at Chalmers University

Klas Andersson, Chalmers University, Sweden

This presentation reviewed the research activities of Chalmers University under the ENCAP project. Primarily, the focus of research is in understanding the:

- Combustion chemistry
- Heat transfer mechanisms
- Fluid mechanics

The 100 kW test rig developed for their oxy-combustion study using dry recycle flue gas was described. The test work undertaken involved:

- Oxy-combustion test using propane
- Oxy-combustion test using natural gas
- Oxy-combustion test using lignite

Results from the gas fired and lignite fired test were presented; and the following results as compared to the air fired case were summarized:

- The temperature level for OF21 (i.e. 21% global O_2 fraction in feed gas) case drops drastically and leads to a delayed burn-out as detected from in furnace HC and O_2 measurements.
- For the OF27 (i.e. 27% global O_2 fraction in feed gas) case, the in-furnace temperature measurements showed very similar profile to the air fired case; of which, it could be noted that together with an increase in O_2-concentration in the recycled feed gas resulted to comparable combustion performance/burn-out behaviour to the air fired case.
- The radiation intensity of the OF27 flame increases with about 20-30% despite similar temperature profiles as compared to the air fired case. This was attributed to possible thermal, chemical and dispersion effects of soot formation in the flame.
- Increased emissivity in the OF27 case is attributed both to the contribution of the increased gas band radiation as well as to the increased soot volume fraction.

Preliminary results of the lignite oxy-combustion test case were presented. The test rig has achieved 1000 hours of continuous operation using lignite as fuel. 300 hours were fired under oxy-combustion condition.

Some of the results presented are summarized as follows:

- Flame temperature:
  - OF27 for lignite fired case compares well to the OF27 for gas fired case in terms of temperature and flame stability. The flame temperature is slightly higher than the air fired case.
  - OF29 has reached a temperature near the ash melting condition (around 1350^{o} C)
  - OF25 results present a rather similar temperature profile in the flame zone as compared to the air fired case.
- Emissions:
  - There are no significant differences in CO emissions between air-fired and oxy-fired cases.
  - Accumulation of SO_2 and NOx were observed in the recycle loop,
  - The measured SO_2 level in the exhaust was reduced to about 40% (in terms of mg/MJ) as compared to the air fired case; whilst, the measured NOx level in the exhaust was reduced to about 30%.
- Radiation intensity
  - Radiation intensities were comparable for Air and OF25 cases – in agreement with the measured temperatures.
  - Radiation increases with decreasing recycle rate.
  - Particle radiation dominates the radiation in both air-fired and oxy-fired cases.

Finally, the presentation concluded with an outlook toward scaling up of current results to the $500kW_{th}$ and $30MW_{th}$ pilot plant studies.

5.5. Stability of Axial Pulverised Coal Flame Under Oxy-Combustion Conditions

Prof. Jost Wendt, Reaction Engineering / University of Utah, USA

This on-going research activity undertaken by Utah University looking at the stability of a Type 0 oxy-combustion co-axial flame was presented. The following points were noted:

- The 100kW down fired test rig to be used for these experiment trials was described.
- The test trials will focus on investigating heat transfer profile and flame stability.
  - The primary task will be looking at the minimum oxygen concentration that would allow stable ignition; and
  - Investigating the effect of oxygen and CO_2 concentration of the primary jet to the flame attachment (an important parameter for NOx control).

Results of previous studies undertaken, based on oxygen enrichment principles looking at the NOx emissions were presented. The previous studies looked at the impact of oxygen enrichment in the transport air, introduction of coal fines and control of wall temperature on NOx emissions. The results based on oxygen enrichment could be summarized:

- NOx emissions could be reduced by promoting flame attachment (up to 64% reduction was observed).
- Promoting flame attachment could be achieved by:
  - Increasing oxygen concentration in the transport air,
  - Introduction of higher level of coal fines,
  - Increasing wall temperature,

The on-going study will make use of the same approach to investigate the impact of flame stability and attachment on a oxy-combustion case with Type 0 flame typically used in corner fired boiler or cement kiln.

5.6. Pilot Scale Experiments Giving Direct Comparison Between Air and Oxy-Firing of Coals and Implication for Large Scale Plant Design

Toshihiko Yamada, IHI, Japan

The on-going study undertaken in the IHI test facility based in Aiolo, Japan was presented. The key points of the presentations were as follows:

- The primary objective of the test programme was to confirm the combustion performance when operating under oxy-combustion mode; wherein at this mode, the heat transfer profile should be similar to the conventional air fired case
- Three types of Australian coal were tested for oxy-combustion trials. Coal A has lower volatile and similar ash content as compared to Coal B; whilst Coal C has lower ash content and high fixed carbon as compared to Coal B.
- The test rig was described in the presentation. It could operate with a maximum of 150 kg/h of coal. The Furnace has an ID of 1.3 m and a height of 7.5 m. The burner used is pulverised coal burner with adjustable swirl.
- The tests undertaken involved the monitoring of the emissions, the flame stability test over a range of thermal loads and the heat transfer profile / flame temperature.

The following results presented could be summarised:

- Heat transfer profile and flame temperature
    - For oxy-combustion mode to have a similar heat transfer profile and flame temperature as compared to air combustion mode operation, it was determined that approximately 27% O_2 concentration should be maintained.
- Emissions:
    - The NO_x concentration when operating at oxy-combustion mode is 60% to 70% lower compared to the air combustion mode.
    - The SO_x concentration is about 30% lower and attributed to a higher sulphation level in the ash.
- Ash Characteristics:
    - Carbon in ash is about 30% to 40% lower during oxy-combustion mode, which was attributed to the higher residence time in the furnace.
    - The ash properties were similar for both oxy-combustion and air-combustion modes.
- A flame blow out was observed when operating oxy-combustion mode at lower load (~60% of full load). It was considered that direct oxygen injection could be used to stabilise the flame when operating at lower load.

5.7. Coal Particle Ignition, Devolatilisation and Char Combustion Kinetics During Oxy-Combustion

Christopher Shaddix, Sandia National Laboratory, USA

A bench scale test under a laminar flow regime was used to investigate the coal particle ignition, devolatilisation and char combustion kinetics when operating under oxy-combustion conditions.
The presentation highlights the following:

- The test rig used is based on a combustion driven entrained flow reactor using a compact diffusion flamelet burner. The particle size, temperature and velocity were measured using a 2 colour pyrometer and a laser triggered image converter camera device (ICCD).
- The test involved, varying the O_2 concentration from 12% to 36% under a N_2 or CO_2 environment.
- Three types of coal tested: the Pittsburgh high volatile bituminous (hvb) coal, High Vale sub-bituminous (sb) coal and Black Thunder sub-bituminous coal. About 1 g/hr of coal was fed into the burner with particle sizes ranging between 75 and 125 µm.

The experimental trials involved the following activities:

- Determination of char kinetic when burning Pittsburgh hvb coal and Highvale sb coal (106-125 µm) in 6% - 36 % O_2 in N_2 at 1400, 1600, and 1800 K.
- Determining the ignition profile of individual particles of Pittsburgh hvb coal and Black Thunder sb coal (75-106 µm) in 12% - 36% O_2 in N_2 and in CO_2 at 1250K and 1700K
    - Measuring ignition time and duration of devolatilisation.
    - Measuring the soot and char particle temperature.
- Determining the combustion profile of Pittsburgh hvb coal and Black Thunder sb coal (75-106 µm) in 12% - 36% O_2 in N_2 and in CO_2 at 1700 K.
    - deriving char kinetics – work in progress

The test results presented the following conclusions:

- Results indicated that both O_2 and CO_2 concentrations affect single-particle ignition, devolatilization, and char combustion processes – considering that the test undertaken removed the macro level impact of flame temperature and radiation.
- Oxygen effects are much stronger than the CO_2 effects.
- The initial heat up profile of the coal particle tested was observed to be independent of O_2 and CO_2 concentration.
- The mechanism describing the effects of CO_2 on particle ignition and devolatilization were presented.
    - The particle ignition time strongly depended on oxygen concentration. The ignition time is slightly longer under CO_2 environment as compared to N_2 environment. For both cases, ignition time is under 10 ms.
    - It could be noted that the mass consumption rate during devolatilisation could be lower under CO_2 environment due to lower diffusivity. This could be observed during trials showing that the duration of devolatilisation of the coal is longer when firing under CO_2 environment and lower O_2 concentration.
- Relative to air, micro scale O_2/CO_2 effects on ignition and devolatilisation approximately cancel each other out for 30% O_2 in CO_2 (similar to macro scale cancelling).
- CO_2 appears to decrease char burning rate, but the data requires further analysis and verification.

5.8. CFD Modelling for Oxy-Combustion Processes

Karin Eriksson, Vattenfall R&D, Sweden

CFD is a useful tool in problem solving and optimisation of air fired cases. Vattenfall believes that a CFD tool would be useful in understanding oxy-fuel combustion.

The presentation highlights the following:

- Commercially available CFD software used for air combustion mode operation was adopted and used for analysis of oxy-combustion mode operation. It was stressed that development and validation of the sub-models under oxy-fuel combustion mode are necessary to provide acceptable results.
- Main parameters to be estimated using the CFD codes are:
    - Heat transfer profile
    - Flame shape and length
    - Emission and char burnout
    - Oxidising or reducing conditions along the furnace wall
- To estimate these parameters, the following sub-models under oxy-combustion mode should be adapted from previous sub-models developed for air combustion and validated against experimental results. These include:
    - Radiation modelling
    - Homogenous gas phase reaction modelling (i.e. gas phase reaction kinetics, NOx mechanisms)
    - Heterogenous reaction modelling (i.e. char combustion kinetics and gasification reactions)

On-going activities in the development of CFD codes undertaken by Vattenfall and its partners were specified and these include:

- Development of gas phase reaction schemes under oxyfuel conditions
- Measurement of soot in oxyfuel combustion and development of soot model
- Coal characterisation under oxyfuel conditions – including gasification reactions
- Validation of models against laboratory coal flames

5.9. Ignition of Oxy-Fuel Flames

Prof. Terry Wall, Newcastle University, Australia

This presentation examined the mechanisms for flame ignition in terms of differing gas properties and gas velocity through the burner. Results obtained from FLUENT™ CFD modelling were compared against the experimental data obtained during trials when operating a thermal load from 480kW to 800kW for air and oxy-fuel combustion cases.

The experimental data are obtained from the trials using Coal A burned in the test rig of IHI as described in the previous presentation by T. Yamada (Section 5.6). The burner was set at low swirl number for both air fired and oxy-fired cases; therefore the resulting flame was a Type 0 flame.

It could be noted that, estimated momentum flux ratio (which is the ratio between the momentum flux of the primary air injection and the secondary air injection) was significantly higher when firing oxy-combustion mode as compared to air combustion mode operating at full and partial load.

The test conditions wherein experimental data are obtained to validate the FLUENT™ CFD model were presented and described.

The CFD model results presented used GAMBIT and FLUENT 6.2 software. The meshing scheme was described to have finer grid near the burner zone. The sub-models used in the FLUENT™ CFD code were enumerated. The coal devolatilisation and char burnout sub-models were based on the experimental data obtained from Drop Tube Furnace experiments.

The FLUENT CFD model presented the following results:

- Temperature field and ignition location
- Velocity field and flow pattern
- Burnout and residence time, heat transfer, and species concentration

All results were validated against the experimental data obtained from the trials. The results of the CFD model compare satisfactorily with the experimental data obtained for the gas temperature profile.

CFD predictions have indicated differences in the:

- Location of the flame ignition. Results showing that ignition when operating under oxy-combustion mode were slightly farther away from the burner quarl as compared to the air combustion mode.

- Burner jet flow significantly varies between oxy-combustion and air combustion cases with the latter having a higher velocity profile and significantly intensive external gas recirculation (see flow contour).

The difference in the flame ignition between oxy-combustion and air-combustion cases was attributed to the difference in the momentum flux and gas properties. The combined effects of both properties defined the flame ignition location. The initial temperature spike observed due to ignition of the fuel could be significantly affected by the swirl number for any Type 0 flames. Higher swirl number was observed to have a temperature spike nearer the burner quarl.

5.10. Thermoacoustic Instabilities in a CO_2 Diluted Oxy-Fuel Combustor

Mario Ditaranto, SINTEF Energy Research, Norway

This presentation illustrated the basic principles of oxy-combustion flame with recycled flue gas for gas turbine application.

The experimental setup for this investigation was described in the presentation. The test rig has the capability to measure the acoustic pressure, CH radical chemiluminescence (heat release rate), velocity using Laser Doppler Velocimetry and temperature measurement at the wall and at the exhaust. The trials investigated the flame stability regime of oxy-gas combustion with flue gas recirculation. It has been noted that typical thermal acoustic instability would result in flame blow out and subsequent flashback. These situations are typically experienced in any air fired pre-mixed type low NOx combustor.

For oxy-gas combustion with flue gas recirculation application, operating under stoichiometric condition presents a sensitive area of combustion profile that could contribute to thermoacoustic instability. However, the variability of controlling CO_2 from the recirculated flue gas as diluents and the O_2 injection for possible local enrichment could provide a possibility of controlling the flame stability by “zoning”. To appreciate such phenomenon, it is essential to understand the chemical timescale and heat release rate toward the thermo acoustic interaction.

This presentation noted that for an oxy-gas combustion flame with flue gas recirculation, three stability regimes could be established dependent on the Reynolds number, equivalence ratio and oxygen concentration. The three regions of stability were explained in great detail. Illustrations of the flame and the parameters affecting such stability regimes were presented.

Finally, the presentation concluded with the following statements:

- Oxy-fuel combustion systems for gas turbine applications offer more complex instability patterns than air supported combustion.
- The increase in burner stability due to local O_2 enrichment can lead to an increase in dynamic instability.
- Knowledge of the flame properties in CO_2/O_2 systems is necessary to predict flame structure.

5.11. Experimental Investigation of Oxy-Coal Combustion at IVD - Using 20 and 500 kW PF Test Facilities

Joerg Maier, IVD – University of Stuttgart, Germany

Research activities on oxy-combustion undertaken by IVD – University of Stuttgart were presented. The primary objectives of the research activity at IVD are focused on understanding the impact of the combustion operation and the impact of re-circulated NO present in the flue gas to the NO_x emission.

The research activities presented included the following:

- Works on fuel characterization (using Klein Kopje bituminous coal and Lausitz brown coal) were investigated using their $20kW_{th}$ drop tube furnace under air-fired and oxy-fired conditions. Information gathered on these experiments was used to set up the boundary condition for combustion modelling.
- On-going work on adapting $500kW_{th}$ test furnace for oxy-combustion operation. Detailed description of the furnace was presented. Preliminary results comparing the emissions of burning pre-dried Lausitz Coal under air-fired and oxy-fired conditions were presented.
- Development of AIOLOS combustion modelling code. The work on adapting the codes which are widely used in modelling furnaces or boilers under air fired conditions was presented. Work on this aspect includes development of various sub-models suitable for oxy-combustion conditions (as enumerated below).
    - heterogeneous char combustion modelling
    - turbulent gas phase reaction
    - radiative heat transfer modeling in CO_2 enriched conditions
    - gas phase combustion modelling
    - NOx formation and destruction

Most interestingly, the results on the impact of NOx emission under staged and un-staged oxy-combustion conditions were noted. It could be observed that the recycled NO resulted in reduction of NO_x emissions of about 46% in un-staged combustion conditions and seems to be dependent on the amount of NO recycled back into the furnace. Approximately 99% reduction of NOx emission in staged combustion conditions was observed and it was noted that NOx emissions were not dependent on the amount of NO recycled back into the furnace. Clearly, the role of NO in the recycled flue gas toward NOx formation and destruction was presented.

Finally, the presentation concluded with an insight to various future works which include:

- Investigation of the impact on combustion of the impurities (Hg, SO_2 etc...) in the recycled flue gas
- Validation of data for combustion modelling with particular stress on char burnout and gas concentration.
- Pyrolysis of coal under CO_2 and N_2 environment.
- Investigation on fly ash quality, and slagging, fouling and corrosion propensity when firing under oxy-combustion conditions.

5.12. Modelling, Design and Pilot-Scale Experiments of CANMET's Advanced Oxy-Steam Burner

Carlos Salvador, CANMET, Canada

The hydroxy-fuel combustion (oxy-steam combustion) concept was introduced in this presentation. The primary objective of this study is to develop next generation burners that could minimise or totally remove the necessity for flue gas recirculation. This research will investigate the feasibility of hydroxy-fuel combustion as a variant of next generation oxy-fuel systems looking at the use of water/steam, preferably with no FGR, to moderate the flame temperature. A prototype burner was developed and was described in the presentation. This burner consists of secondary and tertiary injection ports with independent swirl control, and is capable of burning coal or other fuel with various operating modes which include:

- O_2/steam
- O_2/Recycled Flue Gas
- O_2/CO_2
- Air or Enriched air
- O_2/steam/Recycled Flue Gas
- O_2/steam/CO_2

The experimental rig to test the prototype burner was described. The experimental trials will make use of an Advance Fuel Imagery System to diagnose combustion characteristics of this burner operating under different oxidising gas (comburrent).

5.13. Purification of CO_2 Derived from Oxyfuel Combustion

Vince White, Air Products, UK

The questions of what the quality of CO_2 derived from any oxy-combustion based power plant should be or where to remove the SO_2 and NOx and other impurities, are some of the most important issues which need to be addressed.

The presentation by Air Products illustrated the different options on how to purify the CO_2 rich flue gas produced from any oxy-combustion based power plant. It should be noted that CO_2 derived from oxy-fuel combustion requires purification due to various reasons (i.e. for removal of moisture, inerts removal or compression). If the CO_2 captured is to be used for EOR application, then the O_2 content should be reduced down to less than 100 ppm.

The process design based on a standard cryogenic cycle using two flash column to separate out the inerts from the CO_2 rich flue gas as presented in the previous study commissioned by IEA Greenhouse Gas R&D Programme (IEA GHG Report No. 2005/9) has its limitations namely:

- Removal of SOx and NOx
- Removal of O_2
- Recovery of CO_2 limited by phase separation

However, the recent recognition of possible reactions between NO_x and SO_x in the presence of water during the preliminary compression of the CO_2 rich flue gas prior to water removal was noted to result to production of dilute H_2SO_4 and HNO_3 acids. This would involve a series of reaction steps wherein NO_2 could catalyse the oxidation reaction of SO_2 to SO_3 which then, in the presence of H_2O, could form the dilute H_2SO_4 (lead chamber process). It was further noted that these rates of reaction will be much faster at higher pressure; and HNO_3 will not start to form until all SO_2 has been consumed. Likewise, HNO_3 would also react with Hg. Therefore, it is possible to allow the co-capture of NOx, SOx and Hg during the preliminary compression stage.

With these principles in mind, a new concept for co-capture of Hg, SOx and NOx was presented. Likewise, the new design concepts to improve the recovery and purification (primarily removal of oxygen) of CO_2 were also introduced.

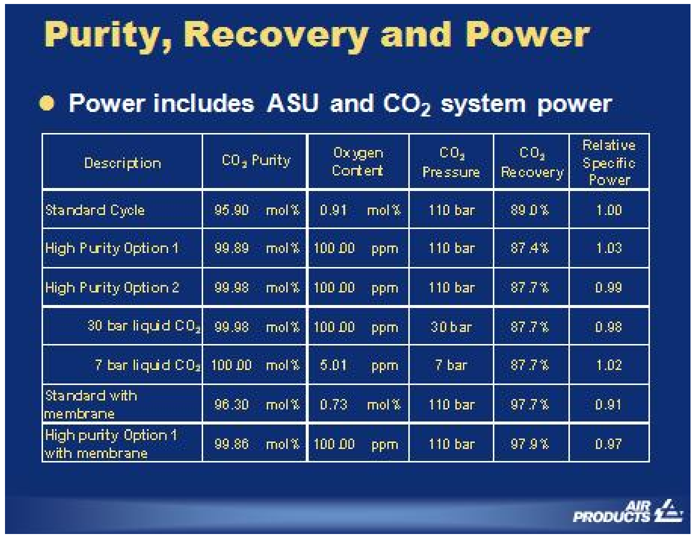
In relation to removal of oxygen, the presentation clearly explained the following basic principles of recovery and purifying of CO_2:

- -55°C is the coldest temperature that could be reach for a viable phase separation
- CO_2 purity would depend on pressure
    - At 30 bar and -55°C, CO_2 purity is 95%;
    - Higher pressure gives lower purity CO_2
- CO_2 recovery would depend on pressure
    - Lower pressure gives lower CO_2 recovery
    - At 15 bar and -55°C, CO_2 recovery is 75%
    - At 30 bar and -55°C, CO_2 recovery is 90%
- CO_2 recovery would depend on feed composition (therefore a reduction of air ingress would benefit CO_2 recovery rate)
    - Increases from zero at 25mol% (wet basis) to 90% at 75mol% (wet basis)

From these principles, it could be concluded that oxygen can be removed down to 100 ppm for EOR-grade CO_2. The presentations presented three different options for removal of inerts/oxygen. In their studies, the following could be summarised:

- Option 1 would involve the removal of the first flash column and with addition of one distillation column operating at 17 bar after the 2nd flash column and prior to compression.
- Option 2 would involve the addition of an extra distillation column operating at 30 bar after the 2nd flash column and compression.
- Option 3 would involve the addition of a membrane in the vent to recover vitiated flue gas that could be recycled back to the boiler.

Their studies presented the following results showing the relationship between purity, CO_2 recovery and relative power demand (as shown in Figure 5 overleaf):



Purity, Recovery and Power

- Power includes ASU and CO_2 system power

Description	CO_2 Purity	Oxygen Content	CO_2 Pressure	CO_2 Recovery	Relative Specific Power
Standard Cycle	95.90 mol%	0.91 mol%	110 bar	89.0%	1.00
High Purity Option 1	99.89 mol%	100.00 ppm	110 bar	87.4%	1.03
High Purity Option 2	99.98 mol%	100.00 ppm	110 bar	87.7%	0.99
30 bar liquid CO_2	99.98 mol%	100.00 ppm	30 bar	87.7%	0.98
7 bar liquid CO_2	100.00 mol%	5.01 ppm	7 bar	87.7%	1.02
Standard with membrane	96.30 mol%	0.73 mol%	110 bar	97.7%	0.91
High purity Option 1 with membrane	99.86 mol%	100.00 ppm	110 bar	97.9%	0.97

Figure 5: Relative power demand, CO_2 purity and recovery of various CO_2 Clean-up Processes

Finally, based on the results of the study done by Air Products, it could be concluded that the addition of a membrane could result in an increase in recovery of CO_2 and reduction of the ASU capacity requirement by 5%.

5.14. Oxy-Fuel Combustion Using OTM for CO_2 Capture from Coal Power Plants

Minish Shah, Praxair, USA

The presentation introduced the application of oxygen transport member (OTM) technology for CO_2 capture from coal based power plants. A schematic diagram describing the OTM application was described.

The process scheme consists of a gasifier producing syngas and this is burned in an advanced partial oxidation reactor (POx) and boiler using OTM to produce electricity. It could be noted that the design of the POx and boiler will consist of banks of OTM tubes interspersed with steam tubes. With this arrangement (i.e. alternate heat source and sink), it is expected that temperature profile will be uniform. Likewise, flue gas recirculation will not be necessary. It is expected that the final CO_2 concentration in the stack would range between 85% to 95% depending on air ingress, and excess O_2 level.

A natural gas fired OTM boiler has been developed and demonstrated successfully. The potential benefits of this application were:

- The use of OTM based advanced boiler concept has the potential of achieving up to 99+% of CO_2 capture
- OTM oxygen separation power reduced by 70% compared to cryogenic process.
- A 4% efficiency gain as compared to conventional oxy-fuel combustion process.
- Low NOx emission without use of SCR.

Finally, the presentation concluded presenting the challenge in the development of OTM application for coal based power plant:

- Achieving high oxygen flux through OTM whilst maintaining reliability
- Technical feasibility of combusting coal-derived syngas using OTM
  - o Looking at the interaction with coal impurities
  - o Investigating the tolerance of the OTM material to the sulphur compounds

- o Understanding the extent of cleanup required before exposing OTM to syngas
- Longer term challenges include the development of:
  - o Manufacturing infrastructure for OTM
  - o Design and engineering of a large scale OTM boiler; and
  - o Reduction of gasifier and boiler costs

5.15. *ITM Oxygen: Progress Toward Reduced CO_2 Capture Cost*

Kevin Fogash, Air Products, USA

The presentation introduced the ion transport membrane (ITM) technology for oxygen production. The development of this technology is aimed to reduce cost and energy requirements for oxygen production as compared to the conventional air separation unit.

The ITM technology is based on a mixed conducting non-porous ceramic membrane typically operated at 800°C to 900°C. The ceramic membrane consists of materials having crystalline structure with oxygen ion vacancies, therefore, allowing oxygen ions to diffuse through to these vacancies. It could be noted that this material is 100% selective for O_2. Development of this technology started in 1999. Current research activities include the commissioning, operation and testing of a 5 TPD O_2 production plant. Preliminary results indicate that performance is well above expectation. The next phase to the development of this technology aims for pre-commercial development and design of the ITM oxygen production plant to be demonstrated. This would include the construction and demonstration of a 25 TPD O_2 production plant and the development of engineering design for a 150 TPD O_2 production plant. The final aim of the development is to scale ITM oxygen production for the FutureGen programme

The techno-economic studies (as shown in Figure 6) indicated that ITM technology requires 35% less capital cost and 35% to 60% less energy for oxygen production compared to a conventional ASU. The performance of ITM as compared to conventional ASU for oxygen production in various applications in terms of capital cost savings and energy savings are summarised below:

	Product		Savings (% of Cryo ASU)	
Application	Oxygen (sTPD)	Power (MW)	Capital for Oxygen	Power for Oxygen
IGCC	3200	458	35%	37%
Decarbonized Fuel†	2400	300	35%	36%
Enrichment*	1500	260	27%	69%
Oxyfuel†*	8030	500	48%	68%
GTL	12,500	n/a	20+%	n/a

†enables carbon capture

*uses existing gas turbine offerings

13 AIR PRODUCTS

Figure 6: Relative performance of ITM in comparison to conventional ASU with respect to various applications.

5.16. Development of Cost Effective Oxy-Combustion for Coal Fired Boilers

Hamid Farzan, Babcock & Wilcox, USA

The presentation described the past and current activities of Babcock and Wilcox in the development of oxy-combustion technology for power generation application. Their past experiences in the development of oxy-combustion include:

- 1979 – did a numerical modelling study on retrofit of power plant with CO_2 capture for EOR application. (Note: The study was required by a major oil company).
- 2000 – as member of the CANMET consortium.
- 2001 to 2006 – development work in collaboration with Air Liquide.
    - Completed oxy-combustion experimental trials firing Ill#6 and PRB coal at their Small Boiler Simulator - SBS (1.5 MW_{th}) facility.
    - Completed techno-economic analysis of oxy-combustion based power plant with CO_2 capture (also in collaboration with Parsons).

Their current activities include:

- Development, construction and commissioning of 2 new oxy-combustion facilities.
    - SBS II facility (based in Ohio) - 2MW_{th} boiler.
    - Clean Environment Development Facility (CEDF) - 30MW_{th} boiler.
- Development of an oxy-cyclone combustion facility.
- Planning and implementation of oxy-combustion experimental campaign for 30MW_{th}.
    - 2nd to 4th Quarter 2007.
- The SaskPower Engineering study.

One of the major programmes to be implemented by B&W is the use of the SBS II facility to investigate oxy-combustion technology for plant retrofit application. This project aims:

- To expand applicability of oxy-combustion to different coal ranks and boiler type.
    - Work will include process optimisation.
    - Oxy-combustion trials firing lignite using conventional wall fired low NOx burner.
    - Oxy-combustion trials firing bituminous coal, PRB and lignite using cyclone boiler.
    - Initiate engineering feasibility study based on wall fired and cyclone unit.
- Investigation of boiler material options for oxy-combustion USC application
    - Perform experiments to evaluate fire side corrosion propensity under oxy-combustion USC boiler conditions.

The 30MW_{th} oxy-combustion test campaign (2nd to 4th Quarter, 2007) was briefly described. The test would evaluate three different coal types (lignite, PRB and eastern bituminous coal) using 1990 design AEROJET DRZ burner. The project aims:

- To demonstrate near full scale burner oxy-combustion trials with on-line pulveriser.
- To develop a new burner concept.
- To develop the B&W novel concept for flue gas moisture control using a wet scrubber and integrated cooling.

Finally, the presentation concluded with short description of support activities to be undertaken by B&W for the SaskPower Oxy-Combustion project which will include the following work scope:

- Boiler selection and data gathering
- Preliminary system design (i.e. ASU design specification and oxygen delivery systems, boiler modification, flue gas processing and compression, CO_2 transport and system integration)
- Economic evaluation

5.17. Doosan Babcock Oxy-Fuel Development Plans

Ragi Panesar, Doosan Babcock Energy Ltd., UK

This presentation described the current oxy-combustion development programme undertaken by Doosan Babcock. Primarily, the development programme would involve three stages namely:

- Stage 1 : Fundamentals and a System Design Study
- Stage 2 : Modified Design Tools and Component Testing
- Stage 3 : Reference Power Plant Design Development

Stage 1 would involve the following studies:

- Oxyfuel safety issues and design guidelines
- Oxyfuel combustion fundamentals (lab & CFD studies)
- Oxyfuel NOx formation (lab & CFD studies)
- Oxyfuel corrosion studies
- Oxyfuel heat transfer characteristics
- Basic design and flowsheets
- Basic efficiency calculations
- Basic costing information

These activities were integrated into the development work funded by RFCS under the Oxy-coal AC project.

Stage 2 would involve the proposal of converting the Multi-Fuel Burner Test facility for oxy-combustion operation. Pending on the UK DTI funding support, the project aims to develop and evaluate full scale burner testing (~ $40MW_{th}$ to $60MW_{th}$).

Primarily, Stage 2 planned activities would incorporate the development of the following:

- Modified Design Tools and Component Testing
- Design rules for combustion efficiency prediction in oxyfuel flue gas
- Design rules for NOx prediction in oxyfuel PF flue gas
- Design rules for furnace and boiler performance in oxyfuel PF flue gases
- Design rules for oxyfuel PF burners
- Continuation of oxyfuel corrosion studies
- Full scale rig test of oxyfuel burner
- Other component testing via participation in the Vattenfall $30MW_{th}$ pilot plant testing

Stage 3 would involve the development of a reference power plant design which includes:

- Development of a full reference design as a basis for commercial plant offering
- Cost of the reference design
- Analyse and predict the availability and reliability of the commercial plant offering
- Analyse and predict the system efficiency and finalise the integration with other equipment

5.18. State of Development of Oxy-Coal Combustion Research Initiative by Fundacion Ciudad de la Energia in Spain

Prof. Vicente Cortes Galeano, University of Seville, Spain

This presentation described the CO_2 capture and storage development programme (including oxy-combustion development project) to be initiated by the Spanish government under the Fundacion Ciudad de la Energia (cooperation between Ministry of Education, Ministry of Energy and CIEMAT).

The Spanish CCS programme aims are:

- To provide support and contribute toward the European R&D efforts in the development of CCS technology.
- To become the focal point for activities in Spain in CCS – bringing together industry, academe and research institution.

The focus of the oxy-combustion test facilities aims to demonstrate the viability of this technology firing low volatile fuels (i.e. anthracite and petcoke). The facilities' design criteria were described, and it was designed to be:

- Modular in nature (i.e. facilities are designed to operate independently).
- Flexible (i.e. possibility to operate a wide ranging activities)
- Extendable (i.e. possible expansion or later stage development)

The test site for the CCS facility has been chosen. The different plant components were described. These include:

- Fuel preparation systems
  - Should be suitable for wide range of coal types (from Anthracite to Lignite)
- Combustion section
  - Consists of two types of boiler with similar thermal load. One boiler will be suitable for oxy-combustion and the other boiler will only be operated as air fired.
  - The boiler will be equipped with U Type furnace (longer residence time) and down fired low NOx burner with variable swirl.
- Flue gas recycle system
  - With recycle capacity between 65% and 75% of the total flue gas.
- Flue gas cleaning section
  - Equipped with SCR, FGD, dust separator and gas cooler.
  - Dust separator consists of hybrid system which includes ESP and fabric bag filter.
- CO_2 compression and transport.
- Utilities and auxiliary units.

The presentation concluded with the proposed time scale for the project (as shown in Figure 7):

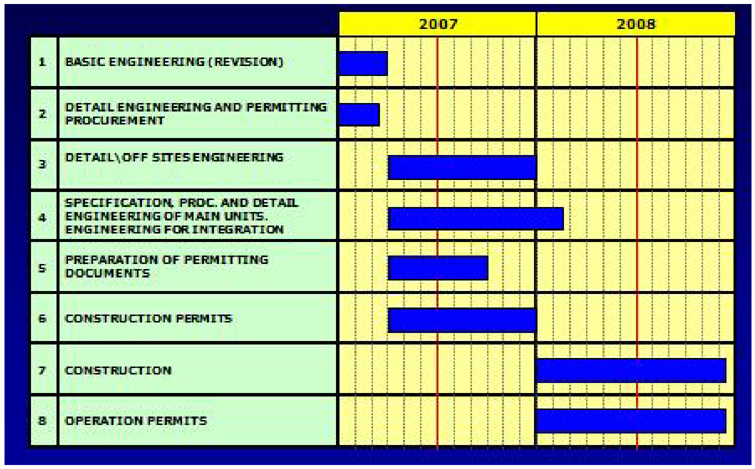


Figure 7: Proposed time schedule for the Spanish CCS Demonstration Project

5.19. Oxy-Fuel Process for Hard Coal with CO_2 Capture – A Part of the ADECOS Project

Prof. Alfons Kather, Technical University of Hamburg-Harburg, Germany

The Oxy-Combustion project undertaken by the Technical University of Hamburg-Harburg funded under the ADECOS programme was described. The primary objective of this project is to develop and evaluate the design considerations of an oxy-combustion process firing hard coal with CO_2 capture. This project will support the Vattenfall Oxy-Combustion Pilot Plant project. Basically, the project aims are:

- To identify key factors that would have significant influence to the decision making steps in any technical feasibility and economic study of any oxy-combustion based power plant.
- To establish realistic design boundaries for evaluation purposes.

The range of interest of various controlling parameters in relation to the operating parameters of the oxy-combustion power plant was identified. These could be summarized as follows:

- The range of interest for the temperature of the recycled flue gas was noted to be between 200°C to 350°C.
- The overall oxygen concentration in the combustion atmosphere was noted to be a function of recycle rate and excess oxygen level. The O_2 concentration rises by reducing the amount of flue gas recycled. To match the heat transfer profile of the air fired case, the oxygen concentration is always greater than 21%.
- The consideration for the quality of the recycled flue gas could be a choice between operating with low dust or high dust loading. The practical pros and cons were identified for the two options.

The main sources of impurities within the oxy-combustion power plant were identified. Its impact to the final concentration of the CO_2 was illustrated. The impurities could be derived from the amount of excess oxygen introduced into the boiler, the amount of other inerts from the oxygen supplied and the amount of air ingress. It was suggested that a target of 1% of air ingress should be set since up to 10% of air ingress could be experienced over the lifetime of the plant. Primarily, it was stressed that the impurities could have some impact to the energy requirement and CO_2 capture rate of the power plant. It was noted that the extent of removing the impurities using cryogenic separation could be limited by the phase equilibrium concentration between CO_2 and the impurities.

The binary phase equilibrium diagram of Ar-CO_2, SO_2-CO_2 and O_2-CO_2; and the ternary phase equilibrium diagram of $O_2 – N_2 – CO_2$ were presented. Experimental results were compared to the modelling results. For oxy-combustion case, where lower purity of CO_2 is required for transport and storage, it was noted that only about 3 % to 4% of the total flue gas treated by the FGD and SCR would be sufficient. For cases where higher purity of CO_2 is required, the power plant design consideration was presented. It was noted that the position of the DeNOx unit within the power plant could be critical and it was suggested that it should be located prior to the flue gas recycle branching.

The presentation concluded with a brief discussion on the power demand for purification of the CO_2 and the impact of the purity of the O_2. The ranges of interest for the operating pressure and temperature of the cryogenic process is shown in Figure 8.

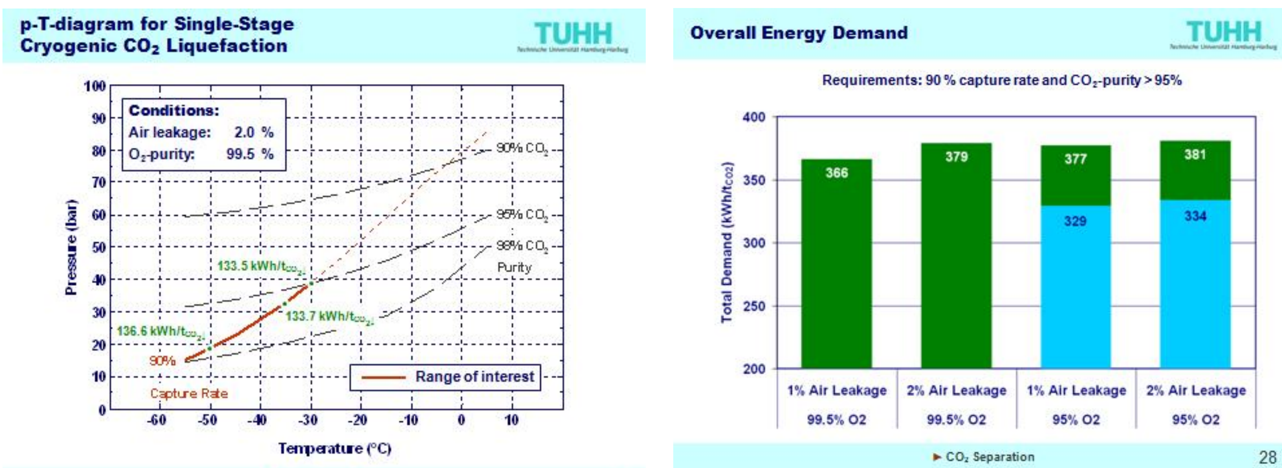


Figure 8: Range of interests (Pressure and Temperature) and it relative energy demand in the CO_2 clean-up process of oxy-coal combustion based power plant

5.20. Development in Chemical Looping Combustion

Tobias Mattisson, Chalmers University, Sweden

This presentation explained the concept of chemical looping combustion (CLC) using gaseous and solid fuel. Primarily, CLC is the combustion of fuel using metal oxides as oxygen carrier. The burning of fuel does not contact air therefore the combustion product is nearly pure CO_2.

The presentation started by explaining the work done and development of CLC at Chalmers University since 2002. It was noted that since then more than 300 studies have been published:

- Looking at the possibility of various materials as the oxygen carrier.
- Development of support materials
- Looking at the possibility of mixing ratios of active and support materials
- Development of construction method for carrier preparation
- Experimental work done using batch reactor, fluidized bed reactors, TGA and continuous CLC reactor.

Some results for active material evaluation were presented and could be summarized below (See Figure 9). Results from TGA apparatus looking at the variations to the metal oxide preparation were presented including some results looking at the reactivity of the metal carrier were presented.

Pros and cons for the active oxides

	Fe	Mn	Cu	Ni
Reactivity	--	-	+	++
Cost	++	+	-	--
Health				-
Thermodynamics				-[1]
Reaction with CH_4			+[2]	
Melting point			-[3]	

[1]maximum conversion 99-99.5%
[2]exothermic reaction in fuel reactor
[3]melting point Cu: 1085 C

Figure 9: Summary of results – metal carrier evaluation.

The 300W and 10kW CLC test rig of Chalmers was described.

Results from the 300W experiments were presented. The investigation focused on reactivity of the 3 different metal oxygen carriers with reaction with the NG. Some of the key observations using this test rig were enumerated. Results of 10kW experiments were noted. This included tests with natural gas and coal. Operational considerations were mentioned. A summary of what has been presented can be seen in Figure 10.

Testing in chemical-looping combustors:

	unit	particle	operation h (hot time[d])	fuel[f]
1	[a]Chalmers 10 kW	$NiO/NiAl_2O_4$	105 (300)	n.gas
2a	[a]Chalmers 10 kW	Fe_2O_3-based	17	n.gas
2b	Chalmers 10 kW	Fe_2O_3-based	16	n.gas.
3	[a]S Korea 50 kW	$Co_3O_4/CoAl_2O_4$	25	n.gas
4	[a]S Korea 50 kW	NiO/bentonite	3[i]	n.gas.
5	[b]Chalmers 300 W	$NiO/NiAl_2O_4$	8 (18)[e]	n.gas
6	[b]Chalmers 300 W	$NiO/MgAl_2O_4$	30 (150)	n.gas/syngas
7	[b]Chalmers 300 W	$Mn_3O_4/ZrO_{2,Mg\text{-}st.}$	70 (130)	n.gas/syngas
8	[c]Chalmers 300 W	Fe_2O_3/Al_2O_3	40 (60)	n.gas/syngas
9	[b]CSIC, 10 kW	$CuO_{impregnated}$	2x100	n.gas
10	[b]Chalmers 300 W	$NiO/MgAl_2O_4$	41 (CLR[g])	n.gas(CLR[g])
11	Chalmers SF[j]	confidential	18	bit. coal

[a]published 2004, [b]published/accepted 2005-2006, [c]submitted [d] total time fluidized at high temperature, [e]same particle as used 100 h in 10 kW unit, [f]n.g. = natural gas, s.g. = syntesgas, [g]chemical-looping reforming, [i]particles fragmentated, [j]10 kW solid fuel CLC,

Figure 10: Range of test undertaken in the 300kW test rig.

5.21. Fixed Bed Membrane Assisted CLC

Sander Noorman, University of Twente, The Netherlands

The evaluation of the feasibility of packed bed CLC as an alternative power production technology was presented. This presentation introduced a packed bed reactor concept for chemical looping application. The work done (i.e. modelling and experiments) was described.

The advantage and disadvantage of the packed bed reactor concept as compared with a fluidized bed concept were noted:

- Disadvantage of a fluidized bed reactor.
  - Recirculation of particles could result to difficult gas-solid separation.
  - Higher propensity of formation of fines.
- Advantage of packed bed (membrane-assisted) CLC:
  - Stationary solids – simple operation could be expected.
  - This involved only periodic switching of gas streams.
  - It is expected that to be dynamically flexible operating in a parallel reactor mode (gas switching system).
  - Could be suitable for natural gas fuel.

The methodology for evaluating the metal carrier reactivity test was explained, see Figure 11:

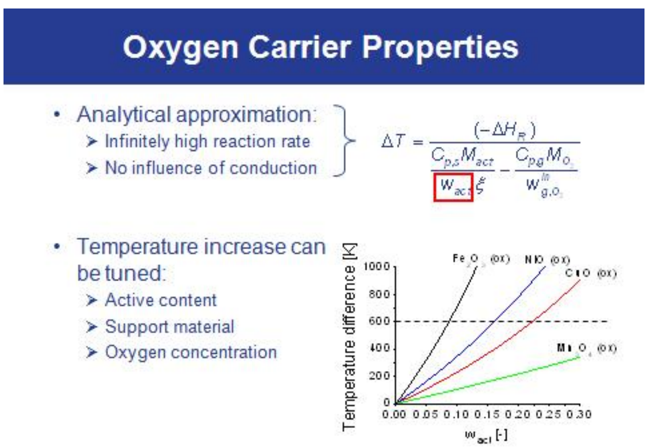
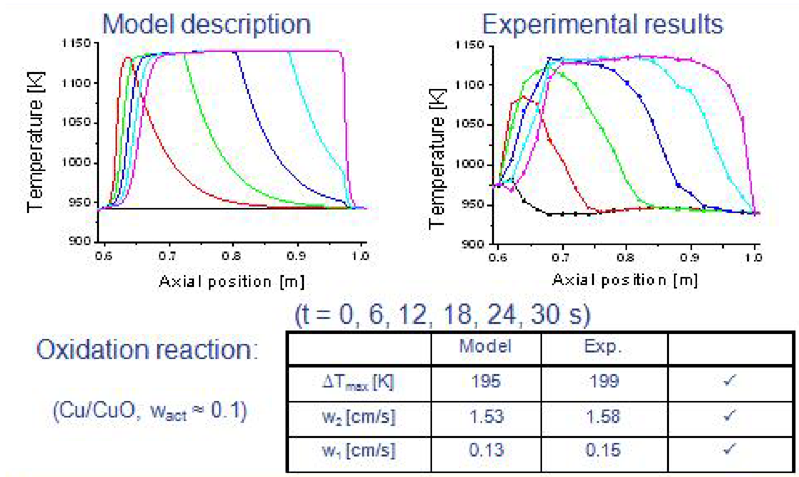


Figure 11: Methodology for evaluating the oxygen carrier properties in a fixed bed reactor

The model results of the packed bed oxidation and reduction cycle were demonstrated. The model validation by using the experiments was described – see Figure 12 overleaf.



	Model	Exp.	
ΔT_{max} [K]	195	199	✓
w_2 [cm/s]	1.53	1.58	✓
w_1 [cm/s]	0.13	0.15	✓

Figure 12: Model results and experimental validation using a fixed bed CLC reactor.

It was noted that the model improvement should include the:

- Correct implementation of the heat losses in the model
- Coupling of the particle model and the reactor model

Finally, the presentation indicated some potential application of this technology in power generation using the combined cycle principle and discussed about the different issues that could be encountered during the design of such a process.

5.22. CLC R&D Efforts of Alstom

Herb Andrus, Alstom Power Inc., USA

This presentation explained the main activities of Alstom in the development of chemical looping combustion. It could be noted that CLC offer good advantage in terms of capturing CO_2. The perceived advantages are enumerated below:

- Potential for > 90% CO_2 capture from coal combustion.
- Low avoided cost of CO_2 capture
- Capital cost – lower than CFB Boiler Island (without CO_2 capture)
- Competitive with Steam Power and IGCC on a worldwide basis

The economic considerations for possible application of CLC as CO_2 capture options were presented (see Figure 13 overleaf).

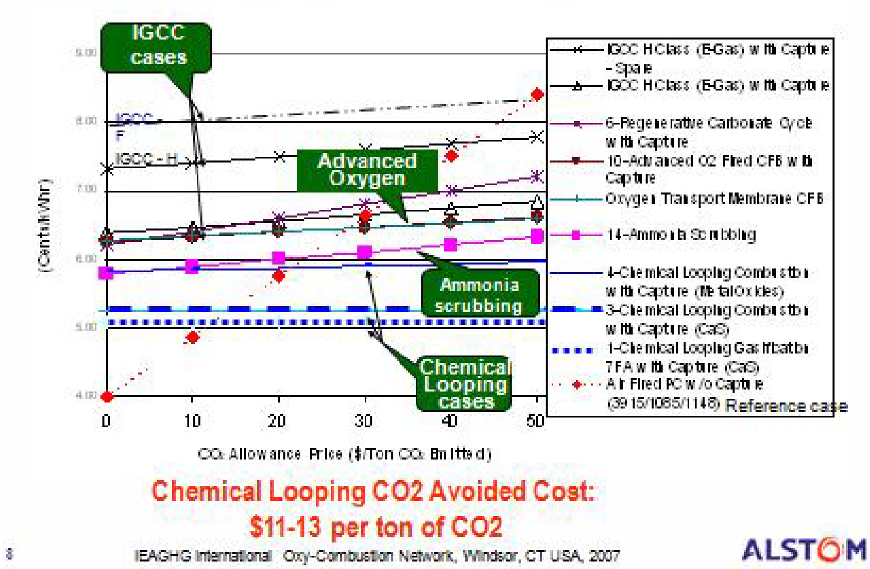


Figure 13: Techno-economic analysis – CLC as compared to other carbon capture technologies.

The technical aspects of CLC application in the power generation industry was noted to be comparable with circulating fluidized bed boiler.

Alstom's involvements in various research activities were presented. Various test facilities were described. Some of their results were presented. These include:

- Involvement with Chalmers University activities using their 10kW pilot plant and 300W process development unit
- Fluidized bed reactor test unit development
- Cold flow analysis

Finally, the presentation was concluded with future development of CLC for gasification application and hydrogen production.

6. SUMMARY OF OPEN FORUM DISCUSSION

The discussion forum was led by Prof. Janos Beer and identified the following points critical to the development of oxy-combustion technology:

- Potential impact to the coal preparation using recycled flue gas as "transport air".
- Variation to the combustion, pollutant formation and destruction mechanisms compared to conventional air fired boiler.
- Experimentally tested models for ignition devolatilisation and carbon burn-out with O_2/CO_2 as the oxidant.
- Burner and boiler design; balance of radiative and convective steam/superheat generation over turn down ranges.
- Flue gas clean-up: for FGR, and for CO_2 compression, pipeline transportation and sequestration.
- Coal type effects on combustion and on corrosion of a PC or USC boiler.

- Dynamic models for start up, turn down and shut down (transfer functions of plant elements).
- New plant PC/USC and FBC/SC?
- Was the retrofitting of existing low efficiency PC boiler feasible?
- ASU plants are expensive and a drain on efficiency, what are the prospects of plant with reduced cost and lower energy demand?
- Commercial size Oxy-fuel demonstration plant? When? What are the conditions?

During the open discussion, the following statements were recorded:

- Power Plant Efficiency Issue:
    - The next generation of lignite fired boilers without fuel drying will have efficiencies of 45% LHV basis. The next generation of lignite fired plants will have fuel drying, which will increase the efficiency from 45 to 49%.
    - The efficiency improvement would be greater for plants with capture because low grade heat could be used for drying.
    - The LHV/HHV difference is particularly large for lignite boilers.

- New Build vs. Retrofit
    - It is better to build a new plant with a high efficiency than a retrofit.
    - There is a lot of sunk investment in moderate efficiency systems. We need to look at mechanisms for including capture in to these systems.
    - Building new plants versus retrofits is often a political decision. There are a range of degrees of retrofit and rebuilding.
    - Because of constraints on equipment supply rapid retrofitting may not be possible. It is best to concentrate on fitting capture to new plants.
    - Plant sites in the US are constrained, after having already fitted FGD and deNOx etc. This is also true in much of Europe. There may be no space to retrofit CO_2 capture.
    - Adding CO_2 capture will reduce the power output, so more replacement capacity will be needed. This makes improvements to efficiency even more necessary.

- Public Acceptance Issue:
    - The public is not discussing CO_2 capture. Getting permissions may be a constraint.
    - There has been significant progress on storage of CO_2, in particular amendment of the London Protocol to include acceptance of CO_2 underground storage.
    - In China, many plants are inland, so overland pipelines will be needed.

- Corrosion Issue
    - Corrosion related issues are important. Increased sulphation of ash was mentioned. A reduction of SO_2 in the flue gas has been seen but not increased sulphur in the fly ash. Is there any sulphation of metals?
    - NETL has an ongoing programme on ash. Attendees were asked to send them oxy-combustion ash.
    - There is more corrosion when high S coals are used, e.g. 4%. With high S coals there is a need to scrub SO_2 before recycling, otherwise the corrosion would be too high.

- Scrubbing recycle gas would add 10% to the efficiency loss. We need to look at materials solutions if we want to have high efficiency.
- High SO_3:SO_2 ratios have been observed in pilot plant work. One coal showed a drastic difference in slagging with oxy-combustion, which could not be predicted. Two other coals showed no difference.

- Issues Relevant to ASU and CO_2 Processing
  - There could be greater integration with oxygen production. There is a need to work closely with ASU suppliers. However, there was bad experience with integration in IGCC plants, resulting in low availability.
  - Perhaps we need to do NOx cleanup before the back end of the plant?
  - Oxygen plants have 99% availability. No spares are needed. There may be some back-up O_2 stored to help for start-up etc.
  - Air cannot be used as a back-up if back-end clean-up of CO_2 is used.
  - There are challenging relationships between gas specifications. What should this group be focussing on?

- CO_2 Purification Issue
  - Impurities in CO_2 are low for post-combustion capture. There may be H_2S in the CO_2 in IGCC but it can be easily removed. According to the presentation by Vince White it is not possible to get much non-inert impurities with oxy-firing, so perhaps CO_2 purity is not a problem.
  - There are already US standards for CO_2 pipelines. There is experience of high H_2S concentrations in Canada but no experience with SO_2.
  - (Comment from NRDC): We want to see technologies mature quickly. There is debate in the US about whether CCS should be regulated. Impurities are an issue. It is important to have certainties. Guidelines would help for design of systems.
  - Impurity concentrations depend on a trade off between capture, transport and storage. It is still an open question which needs resolving. There is a need to agree specifications for pipeline grids.
  - The power industry will not operate the infrastructure for CO_2 transport and storage.
  - The optimum O_2 purity was discussed. Increasing the O_2 purity above 95% significantly increases the power consumption, but reduces the back-end clean-up. 98+% O_2 purity will be used in the Vattenfall plant. It is difficult to remove Ar from O_2 but also from CO_2. A high oxygen purity enables a high overall percentage CO_2 capture.

7. SUMMARY OF PANEL DISCUSSION

The panel discussion was led by Dr. Sho Kobayashi. The objective of this discussion was to present the current status and future development of large scale demonstration of the oxy-combustion technology.

The discussion started with Dr. Kobayashi presenting a historical view on the development of oxy-combustion for boiler application and indicated what could be an important milestone in the development of this technology (As shown in Figure 14).

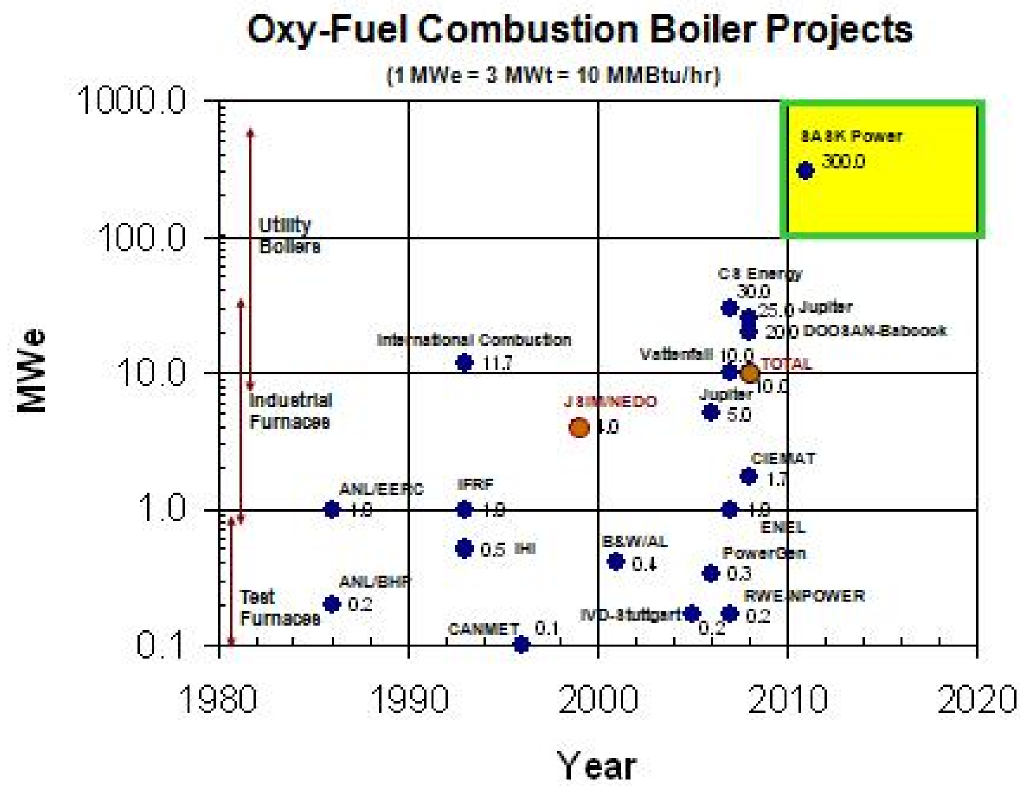


Figure 14: Historical perspective in the development of oxy-fuel combustion boiler projects.

7.1. Coal-Based Oxy-Fuel System Evaluation and Combustor Development

Leonard Devanna, Clean Energy System, USA

The CES Oxy-Combustion Technology was briefly described. Development milestones from successful operation of their 110 kW_{th} bench scale unit to the development of their 5MWe Kimberlina facilities were presented (including development of a 20MW_{th} burner).

These activities could be summarized below:

- 2001: Test completed using 110 kW_{th} CES oxy-combustion burner system. Project funded by the California Energy Commission.
- 2002: Development and design of 20MW_{th} CES oxy-combustion burner system. Project funded by the US DOE/NETL Vision 21 programme
- 2003: Acquisition of Kimberlina Power Plant (5MWe); supplemental funding from California Energy Commission was awarded for its development
- 2005: US DOE funded development of oxy-syngas combustion using CES process. Work in collaboration with Siemens.

Development of CES Oxy-Combustion Technology application for coal based power plant was introduced. The concept involved the gasification of coal and the use of syngas as fuel for the CES oxy-combustion technology (see Figure 15).

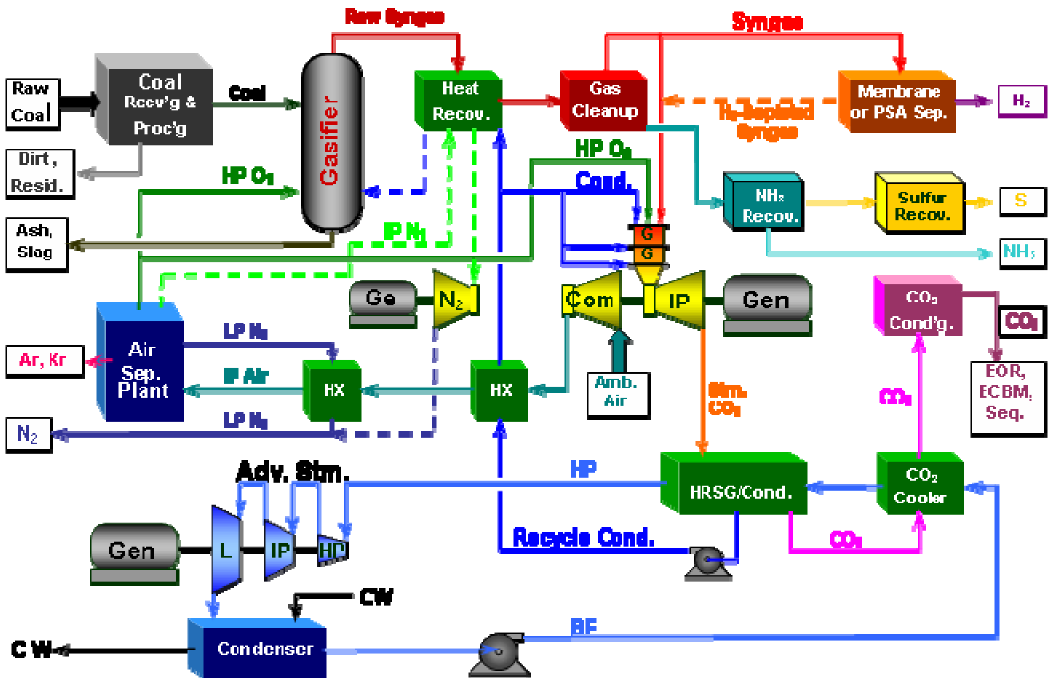


Figure 15: Schematic diagram of the coal based CES Oxy-Combustion Process.

Finally, the future project involving the partnership with Southern California Gas Company building the ZEPP-1 (~50MW) power plant was introduced. It was expected that commercial operation would start between 2008/9.

7.2. Oxy-Combustion and CO_2 Storage Pilot Plant Project at Lacq

Nicolas Aimard, Total, France

Total presented their activities regarding the Lacq Pilot Plant Project (involving an integrated capture, transportation, injection and storage project) indicating their main commercial motivation:

- To evaluate and assess options of reducing greenhouse gas emission during the production of Extra Heavy Oil using the steam assisted process.
- To develop experience and knowledge on CO_2 storage into a depleted reservoir pilot (modelling, monitoring)
- To assess the Lacq field potential for long term and larger scale CO_2 storage

The capture project would involve the retrofit of existing oil fired steam production plant (boiler) with oxy-combustion technology (As shown in Figure 16).

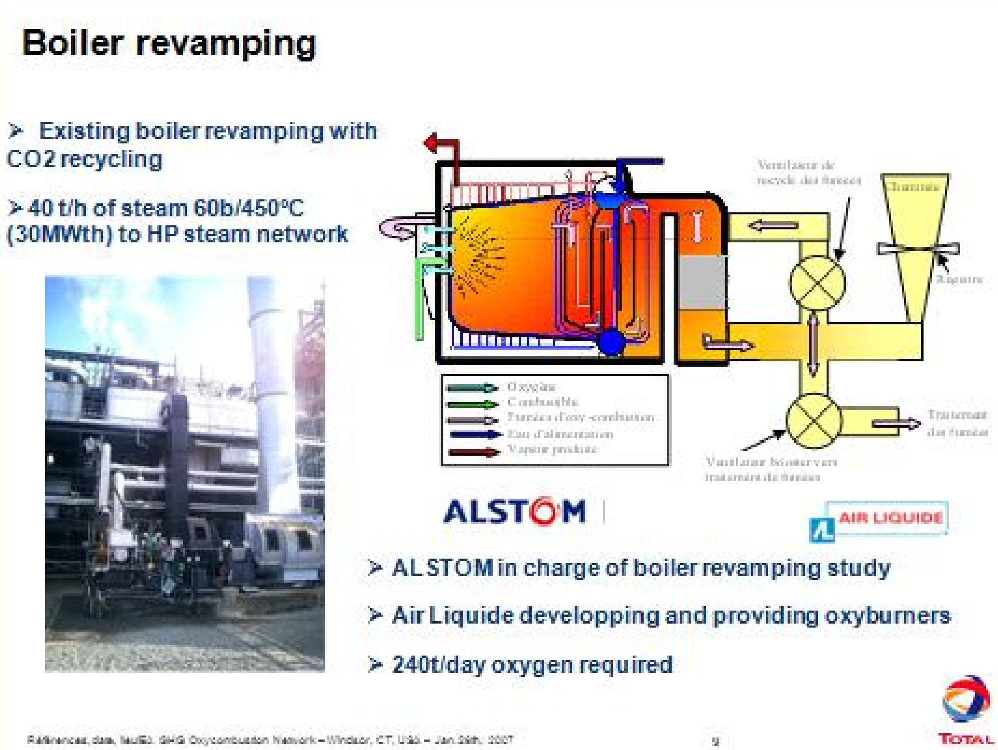


Figure 16: Schematic diagram of the boiler to be retrofitted with oxy-combustion for the Laqc project.

The study will include the following activities:

- Development of industrial scale 30MWth oxy-combustion unit with gas
- Revamping of a 35MW+ conventional boiler
- High sulphur liquid fuel to be tested in the second phase
- First CO_2 injection for storage in France
  - o 150 kt CO_2 storage in a depleted reservoir

It was noted that due to lack of French or international legal framework, it was decided that the CO_2 transport and injection into a Lacq satellite would be limited only to 2 years.

The boiler revamping will be managed by Alstom. The burner development will be supplied by Air Liquide using 4 x 8MW_{th} dual fuel burners as shown in the slide.

The following considerations in the design of the plants were noted:

- SOx content and its impact
- Pressure of the boiler
- Drying of the CO_2
- Consideration for de-rated operation
- Environmental impact assessment

The project will be commissioned in the later part of 2008. The project schedule is shown in Figure 17 below:

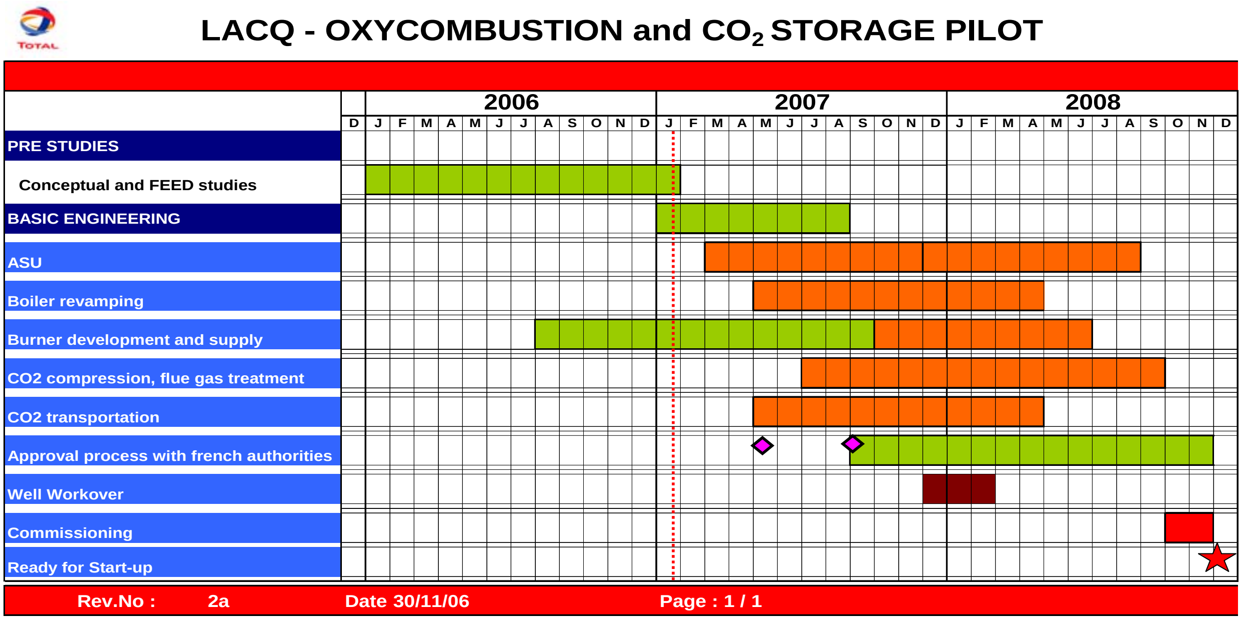


Figure 17: Schedule of the Lacq Pilot Plant Project

7.3. The Saskatchewan Advantage: SaskPower Clean Coal Project Update

Bob Stobbs, SaskPower, Canada

SaskPower presented its motivation towards the development of its clean coal project. It could be noted that there is an economic opportunity toward the development of clean coal power plant with CO_2 capture by recognising the fact that two products could be produced namely electricity and oil via CO_2 flooding.

The economics of building the clean coal power plant with CO_2 capture was explained. It clearly pointed out the uncertainly of the value of carbon that could possibly impact the viability of the project.

An overall view on the environmental and sustainability assessment was presented.

The project schedule is presented in Figure 18. The results of the business case analysis will determine the final decision by Saskpower for the project to proceed.
The SaskPower Clean Coal Project Proposal (end June 2007) will include:

- Business case analyses addressing cost, risk and revenue expectations
- Provisional equipment and construction contracts for immediate acceptance
- Provisional CO_2 sales agreements for immediate acceptance
- Project Execution Plan

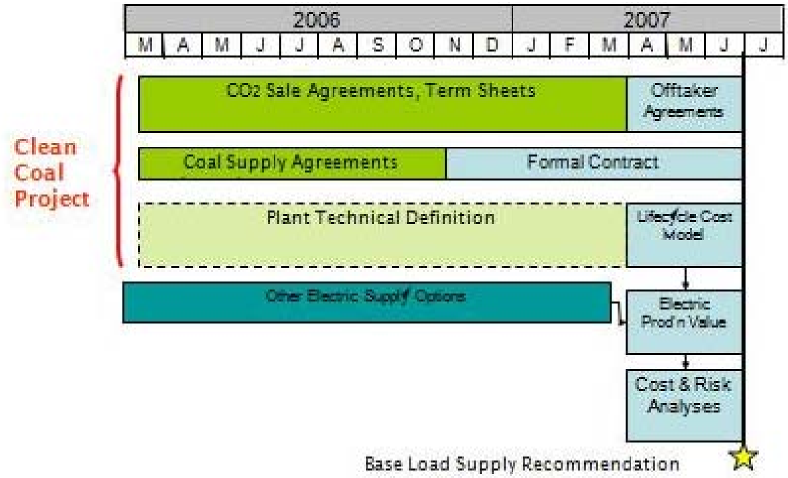


Figure 18: Schedule of the SaskPower demonstration project

Provisional EPC contract has been announced:

- Boiler — Babcock & Wilcox
- Air Separation Unit — Air Liquide
- Compression & Purification Unit — Air Liquide
- Steam Turbine Generator — Marubeni/Hitachi
- Owner's Engineer — Neill & Gunter
- Balance of Plant — TBD

7.4. Callide-A Oxy-Fuel Project Status

Chris Spero, CS Energy, Australia

The Callide Oxy-Fuel Project update was presented. This included:

- Project milestone achieved
- Boiler assessment activity including plant condition assessment and design review
- Burner requirement assessment and modification development
- Project scope

The project schedule is shown in Figure 19:

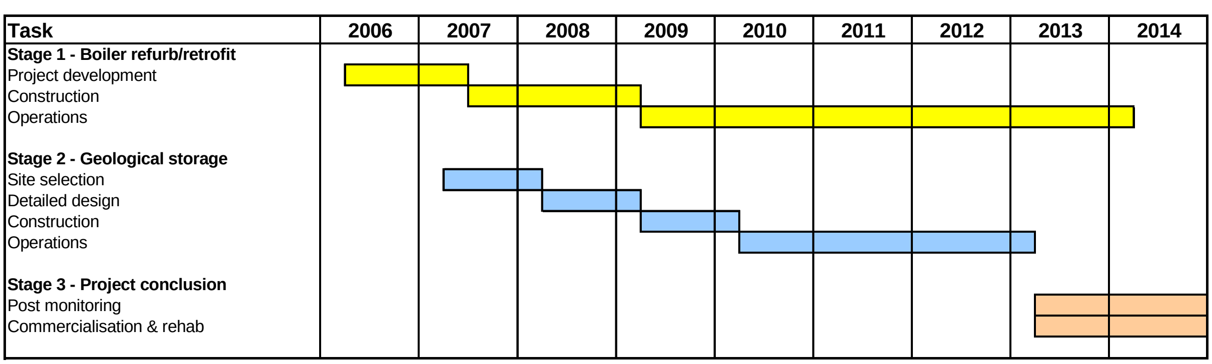


Figure 19: Schedule of the Callide demonstration project

The project was designed to achieve the following milestone (as of start of 2007):

Date	Milestone
Sep. 04	Feasibility study MOU signed ($1.3 million cash + in-kind)
Sep - Dec. 05	Pilot-scale tests conducted in Japan (addition $350,000 funding obtained)
Mar. 06	Demonstration Project MOU signed Low Emission Technology Demonstration Fund Application submitted
Jul. 06	Feasibility study completed
Oct. 06	• Funding announced by Commonwealth Government ($50 million) • Callide plant condition assessment completed (CBH, Siemens, IHI, Auspower, Energen)
Nov. 06	Preliminary design and hazard review completed (CS Energy, IHI, Gas Plant supplier)

The current plant / boiler condition was briefly described. It could be noted that evaluation result indicated a better than expected condition. Burner development was also described and summarized as shown in Figure 20 below:

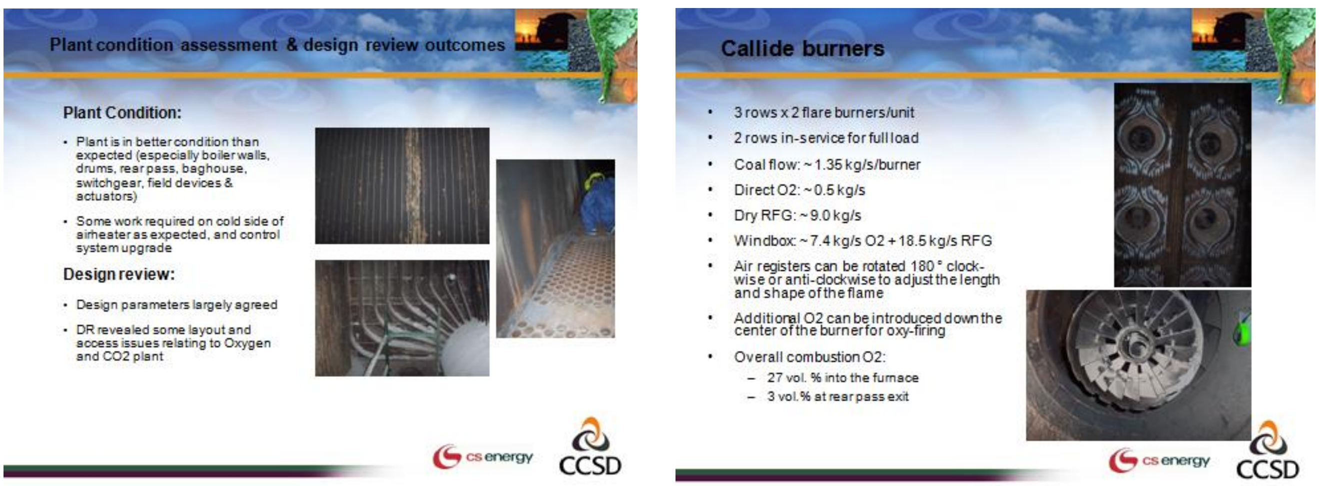


Figure 20: Current boiler conditions and burner configuration.

Project scope includes the following:

- Nominal 660 tpd O_2 supply (@ 98% purity)
- Overhaul and refurbishment of 1 x 30 MWe boiler/STG
- Retrofit of boiler for oxy-combustion and flue gas recirculation
- Flue gas processing and CO_2 capture (80 – 100 tpd)
- Road transport of up to 100 tpd CO_2 (max)
- Geological storage (~100,000t over 4 years)

7.5. CO_2 Free Power Plant Project: Status Oxy-Fuel Pilot Plant

Lars Strömberg, Vattenfall AB, Sweden

Vattenfall stressed their commitment toward development of carbon mitigation. It could be noted that they believed that currently oxy-combustion is their most attractive option at this time but they would not discount other technology options.

Prof. Lars Stromberg presented a roadmap on the development of oxy-combustion with an aim to demonstrate the technology by 2015 and for commercial operation by 2020. They considered their 30MWth pilot plant as a stepping stone toward these goals.

Vattenfall aims to use the pilot plant as a platform:

- To demonstrate the process chain.
- To investigate the interaction of the different components
- To validate the basic design and scale up criteria
- To understand the long term dynamic process

As of January 2007, the ground had been cleared for construction. The figure below illustrates the different statuses of the component packages (See Figure 21).

Status – Component Packages

Order - lot	Supplier	Included components	Status
Boiler	Alstom	Boiler, ESP, preheater, fans, FG-ducts, stack, coal-/ash-silo	Detailed engineering
FGD	Babcock Noell	Flue gas cooler, FGD	Detailed engineering
FGC	TREMA	FGC	Detailed engineering
ASU	Linde	ASU, O2-Stand-by-system, N2	Detailed engineering
CO2-processing	Linde	CO2-cleaning, -liquefaction, back evaporation, intermediate storage	Detailed engineering
Cooling tower	GEA	Cooling tower	Detailed engineering
I & C	Siemens	Main instrumentation, control	Order Jan 2007
BOP	MCE, Berlin/CB	Pipes, fittings, pumps, insulation, Tanks, Compressed air station	Order dec 2006 Planning
Civil/Shell	OBAG Bautzen	Underground pipes, foundations, ways, building	Order dec 2007 Planning

Figure 21: Status of the different work packages (as of January 2007).

Prof. Stromberg also mentioned about their experience on their environmental permitting process. Its status is shown in Figure 22 (As of January 2007):

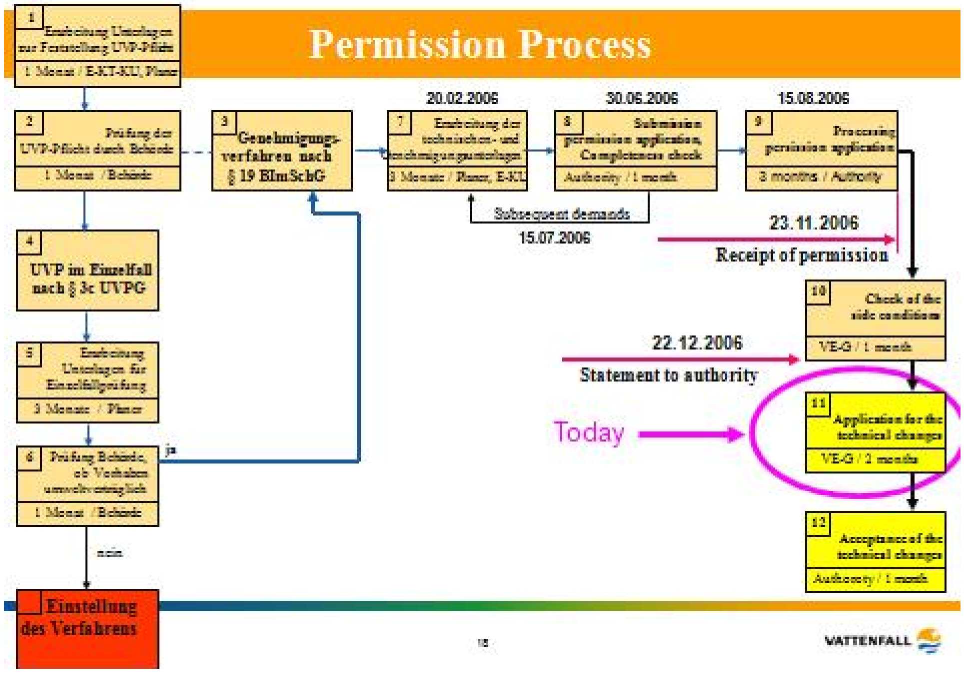


Figure 22: Permitting process (as of January 2007).

The schedule and status of the project (as of January 2007) is given in Figure 23:

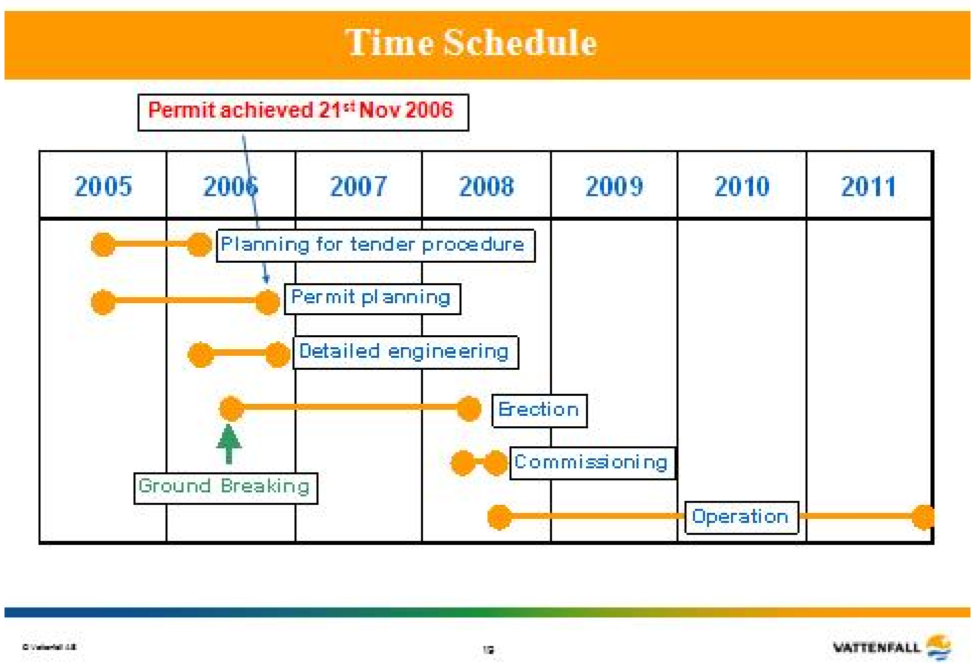


Figure 23: Schedule of the Schwaze Pumpe pilot plant project.

Regarding to the status of the captured CO_2, it could be noted that it is of high quality that could be stored anywhere or sold in the commercial market. The CO_2 captured from the pilot plant is classified not as waste but as a product. Prof. Lars Stromberg noted that several storage options are being examined at present and they anticipate having the CO_2 storage components be ready by the time that considerable amounts of CO_2 start to be produced.

Finally, the presentation concluded with the following statements:

- Present total budget is estimated at close to 70 million € for the investment in the plant and 23 million € for operating costs during the test period. Vattenfall has taken decision to finance the Pilot Plant fully. There is presently no public funding at all
- Vattenfall have invited partners to participate and utilise the facility and contribute to the funding.
- Vattenfall is currently seeking partners for the storage option.

7.6. Moving Oxy-Combustion Forward:- Overview of Jupiter Oxygen's R&D Activities

Brian Patrick, Jupiter Oxygen, USA

This presentation described the current oxy-combustion development undertaken by Jupiter Oxygen. Previous testing experience and experimental trials were discussed. It could be noted that their trials indicated fuel savings and reduction in NOx if operating as standalone process.

Results taken when operating with integrated pollutant removal system developed by NETL were presented.

- Capture of 80% CO_2; when operating at pressure would capture up to 90%.
- 60% to 90% mercury removal
- 99% sulphur removal
- 99% particulate removal and 80% removal of $PM_{2.5}$.

The facility in Hammond was described. Major components of the plant include the combustion chamber, 105 TPD cryogenic ASU plant (producing 95% purity), coal pulveriser, and automated data acquisition system.

The test programme was explained. This will involve single burner testing, flame stability test, and evaluation of the integrated pollutant removal system.

The Orville Retrofit Project was introduced. The boiler to be retrofitted was built by Combustion Engineering and was installed in 1969. The boiler was installed with a pressurized regenerative air heater and ESP; RO front wall fired burners with gas igniter, coal pulverisers and 25MW steam generator. It was noted that the Orville project would also include a facility to allow a slip stream for testing the integrated pollutant removal system.

Finally, the presentation concluded with a brief discussion of their economic assessment work.

7.7. PANEL DISCUSSION

Below are some of the discussions highlighted during the forum:

- The advantage of oxy-combustion over IGCC was discussed. It was noted that if greater than 95% CO_2 capture is required, oxy-combustion may have more potential than IGCC.

- Uncertainties in cost estimates were highlighted. Costs tend to increase and real cost figures are still not known. All technologies are improving, e.g higher GT temperatures and >700^{o}C steam turbines. It is difficult to compare systems which do not yet exist.
- PC boilers have excellent availability. Utilities are very hesitant to introduce technologies which will be less reliable. IGCC has the advantage of being able to produce hydrogen, which may be valuable in future in the transport sector.
- Regarding the SaskPower oxyfuel plant, it was said that it was virtually impossible to find a technology supplier for IGCC for lignite. The technology guarantees were better for oxy-combustion than for post-combustion.
- Chemical looping combustion was discussed. This avoids the high energy consumption of oxy-combustion. CFB boiler experience can be used but use of sophisticated bed materials for coal is a concern.
- Coal has a variety of properties, which will affect the choice of optimum technology.
- The issue of air ingress and its impact on CO_2 clean-up was discussed. Oil boilers are run at positive pressure but there are safety challenges for large boilers. Ancillaries such as air heaters and fabric filters are major potential sources of leakage. Manufacturers could build gas tight boilers – for a price. CO_2 processing was said to be the biggest unknown in oxy-combustion processes.

8. SUMMARY AND CONCLUSIONS

The workshop covered a wide range of topics from current on-going studies and experimental results to development of new technology for oxygen production and CO_2 processing; and up to date briefing on the status of different large scale oxy-combustion demonstration and pilot plant projects.

This section summarised the main points of discussion and identifies briefly the current state of the technology and the different issues important to the development of oxy-combustion process for power generation with CO_2 capture.

The future directions for the development of the oxy-combustion technology would have three different legs namely:

- The short term development of the oxy-combustion technology would look at the enabling technologies that would be suitable for plant retrofit or new built; and would be totally based on the current conventional power plant equipped with new highly efficient and air-tight boiler. This type of boiler could also allow operation of the boiler based on air firing mode. (i.e. Projects developed by Vattenfall, CS Energy/IHI and TOTAL)

- The intermediate term development of the oxy-combustion technology would look at enabling technologies that would build the next generation power plant purposely for oxy-combustion. It could be perceived that this type of boiler would still be similar to the current conventional boiler but never planned for air firing. (i.e. CANMET development in HYDROXY Burner)

- The longer term development of the oxy-combustion technology would look onto new technologies that would be totally different from the current conventional boilers (i.e. Chemical Looping Combustion, Praxair's OTM membrane, CES technology).

For the short term development of oxy-combustion process, the following points could be highlighted:

- Validated simulation of the oxy-combustion process will be the key to allow plant retrofit with confidence. It is important to establish how to extrapolate what has been learned (i.e. sub-models developed) for an air fired case to oxy-fired case.
    - There is still a need to develop simulation tools that would allow modelling of heat transfer, ignition, devolatililisation and char burnout kinetics, and ash partition and deposition.
    - Particularly, there are still a lot of uncertainties in the understanding of impact of ash deposition to the heat transfer model. This also includes the gap of knowledge in the gas to surface thermal resistivity.

- It could be identified that there is a critical gap of information on the ash deposition and its impact to the fireside of the boiler (i.e. corrosion).
    - There is limited information on particle deposition and slag formation under oxy-combustion firing mode.
    - Critically, it is important to note that further data should be gathered to establish the relationship between flue gas recycling, impact of CO_2 rich environment, recycling of SOx and NOx to the deposition and slag formation (which are also dependent on coal types).

- There is already a good understanding in NOx and SO_2 formation (including sulphation of the ash). However, there is still a need to obtain more data for SO_3, Hg and trace metal emissions.
    - It is well accepted and established that recycling of flue gas containing NOx species could reduce NOx emissions (on mass emissions basis).
    - The reduction in NOx was primarily attributed to the reburn mechanism.
    - It could be established that there is about 30% reduction in sulphur emission due to higher sulphation rate of the ash promoted by the ash's Ca content.
    - There is still some uncertainty on the SO_2 concentration that can be tolerated in the recycle loop, and whether desulfurization before recycle is necessary for high sulfur coals.
    - Likewise, there is some indication that SO_3 formation could be potentially higher during oxy-combustion. But further data should be obtained to validate such an indication. It should be noted that understanding of SO_3 formation is important to the operation and estimating the performance of downstream units (i.e. ESP and Fabric filter operation – primarily its implication to the dew point temperature).
    - The issue of air ingress is very critical to the viability of oxy-combustion process.
        - The limit on non-condensables is driven by the limit on the physical separation process and the cost of separating these impurities from CO_2

during compression. (This would definitely impose the severe constraints on furnace inleakage or air-ingress for plant retrofit).

For the intermediate term development of oxy-combustion processes, the very focus of the research would be in the aspect of reduction (or elimination) of externally recycled flue gas. This could be achieved by use of steam as the attemperation medium or application of combustion techniques applied in the glass furnaces (i.e. high velocity jet burner / flameless combustion technique).

- The critical barrier to such developments are identified which are:
  - Furnace / boiler materials selection.
  - Understanding the aerodynamics of directed O_2 injection point.

- Simulation tools necessary to aid boiler / furnace developments are essential.
  - Heat transfer that would allow flame temperature cooling (including the prediction of aerodynamics and temperature profile differentiated by high jet injection of oxygen and fuel).

The longer term development would probably involve the development of techniques and processes that could reduce the energy penalty from oxygen production. There are two main common development issues in any types of oxy-combustion technologies.

- To address the energy penalty related to the oxygen production
- To address the requirements for the CO_2 quality

The longer term development addressing the energy penalty due to oxygen production would include:

- Development in chemical looping combustion

- Development and integration of alternative oxygen production system
  - OTM (development undertaken by Praxair)
  - ITM (development undertaken by Air Products)
  - CARS (development undertaken by BOC / Linde)

Efforts in the development of the oxygen production could be subdivided into two directions:

- Near term development would look onto the improvement of current cryogenic distillation process:
  - What could be the optimum oxygen purity in terms of minimising the CAPEX and the OPEX?
  - What are the potential for integration with the boiler island and the CO_2 processing unit?
  - What could be the permissible maximum capacity of current ASU cryogenic technology? (i.e. Could we have a single train ASU that could produce greater than 5000 TPD O_2?)

- Medium to long term development would look into the development of various breakthrough technologies: (It should be noted that this leg of development would be a merger between the long term development of oxy-combustion boilers / furnaces and oxygen production). Breakthrough technologies include:

- Development in membrane technologies (i.e. ITM, OTM, CARS)
- Chemical looping combustion process (no oxygen production required)

It is important to discuss the issue of CO_2 purity. It should be noted that concentration limits for on-site storage are uncertain, both technical and regulatory.

- Would the CO_2 rich products be considered as a waste? or as a resource?

- What are the requirements of the CO_2 storage site with regard to the major impurities (i.e. O_2, N_2 and Ar)

- What are the different technical issues involving the removal of minor impurities (i.e. SOx, NOx, Hg and other trace metal)?

The compression and condensation process proposed by Air Products is considered one of the most elegant solutions for CO_2 processing presented during the workshop. It is important to note that possible reaction between NOx and SOx during the compression stage of the CO_2 rich product is considered an important learning. However, the reaction mechanisms and capture efficiency of these minor impurities should be further verified.

Farmington River Bridge, Windsor, CT

2nd Oxy-fuel Combustion Network Meeting

25th-26th January 2007

Hilton Garden Inn, Windsor, Connecticuct

Organised by

IEA Greenhouse Gas R&D Programme.

Hosted by

Alstom Power

Objectives

Provide scene setting overviews
Feedback from participants
Review of new initiatives on oxy-combustion R&D activities.

Program Highlights

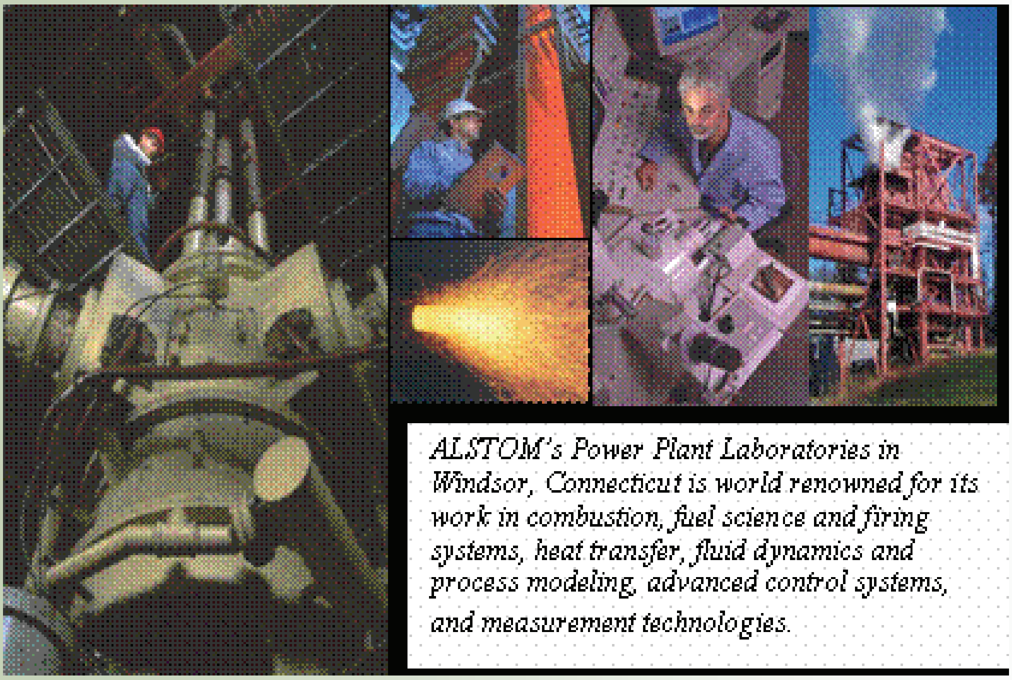
Wednesday: Visit to Alstom's 3MW Oxy-CFB and CLC test rig.
Thursday: Disscusion Forum on Various Oxy-Combustion Technical Issues.
Friday: Panel Disscusion on Large Scale Pilot Demonstration Projects.
Monday: Optional visit to CANMET Oxy-Combustion Facilities

ALSTOM

23rd January 2007

1500 to 1800 Visit to ALstom's 3MW Oxy-CFB and CLC test rig

ALSTOM



17.00 Welcome Drink at Alstom Facility

18.00 to 19.00 Pre Registration at Hilton Garden Inn Reception Hall

25th January 2007 Day 1

08.30 to 09.00 Welcome Address-Alstom Power Inc; John L. Marion VP Global Technology- Boiler Business, USA
IEA GHG-Background to International Oxy-Combustion Network; John Topper MD IEA Greenhouse Gas R&D Programme.

Session 1-Keynote Presentations; Chair;John Topper

09.00 to 09.40 Overview of Oxy-fuel Combustion Technology:Progress and Remaining Issues; Adel Sarofim, University of Utah, USA

09.40 to 10.20 An Overview to Alstom's R&D Activities on Oxy-Combustion Technology Application for Power Generation Industry; Woody Fiveland, Alstom Power Inc, USA

10.20 to 10.40 Break

Session 2a- Oxy-Combustion Experimental Study and Modelling, Chair; Klaus Hein

10.40 to 11.00 Combustion Tests and Modelling of the Oxy-Fuel Process-an Overview of Research Activities at Chalmers University; Klas Andersson, Chalmers University, Sweden.

11.00 to 11.20 Stability of Axial Pulverised Coal Flame Under Oxy-Combustion Conditions; Jost Wendt , Reaction Engineering/University of Utah, USA

11.20 to 11.40 Pilot Scale Experiments Giving Direct Comparison Between Air and Oxy-Firing of Coals and Implication for Large Scale Plant Design; Toshihiko Yamada, IHI, Japan.

11.40 to 12.00 Coal Particle Ignition, Devolitisation and Char Combustion Kinetics During Oxy-Combustion; Christopher Shaddix, Sandia National Laboratory, USA

12.00 to 12.20 CFD Modelling for oxy-combustion process; Karin Eriksson, Vattenfall R&D, Sweden.

12.20 to 13.40 Lunch

Session 2b- Oxy-Combustion Experimental Study and Modelling, Chair; Klas Andersson

13.40 to 14.00 Performance of PF Burners Retrofitted to Oxy-Firing; Terry Wall, Newcastle University, Australia.

14.00 to 14.20 Thermo Acoustic Instabilities in a CO_2 Diluted Oxy-Fuel Combustor; Mario Ditaranto, Sintef Energy Research, Norway

14.20 to 14.50 Experimental Investigation of Oxy-Coal Combustion at IVD using 20 and 500kw Test Facilities; Joerg Maier, IVD-University of Stuttgart, Germany.

14.50 to 15.10 Modelling, Design and Pilot Scale Experiments of CANMET'S Advanced Oxy-steam Burner; Kourosh Zanganeh, CANMET, Canada

15.10 to 15.30 Break

Session 3- CO_2 Processing, Oxygen Production and Membrane Technology, Chair; Jean-Pierre Tranier

15.30 to 15.50 Purification of CO_2 from Oxy-Fuel Combustion; Vince White, Air Products, UK.

15.50 to 16.10 Oxy-Fuel Combustion using OTM for CO_2 Capture from Power Plants; Minish Shah, Praxair, USA.

16.10 to 16.30 ITM Oxygen: Progress Toward Reduced CO_2 Capture Cost; Kevin Fogash, Air Products, USA

Session 4 -Open Forum: Chair; Janos Beer

16.30 to 17.30 The remaining issues for oxy-combustion technology
- Summary to day 1 presentations
- Discussion on various issues relevant to development oxy-combustion technology
1. Boiler and burner development
2. Oxygen production.
3. CO_2 Processing.

Close Day 1
19.00 Dinner sponsored by Alstom Power Inc.

ALSTOM

26th January 2007 Day 2

08.20 to 08.30 Administrative Announcement

Session 5 -On-Going Oxy-Combustion Studies; Chair Jost Wendt

08.30 to 08.50 Development of a Cost Effective Oxy-Combustion Coal Fired Boiler; Hamid Farzan, Babcock & Wilcox, USA.

08.50 to 09.10 Application of Oxy-Fuel Technology for Retrofit/New Build Power ; Ragi Panesar, MBEL, UK

09.10 to 09.50 State of Development and Results of Oxy-Coal Combustion Research Initiative by Fundacion Ciudad de la Energia in Spain; Vicenté Cortes, School of Engineering, University of Seville, Spain.

09.50 to 10.10 Oxy-Fuel Process for Hard Coal with CO_2 Capture-a part of the ADECOS project; Alfons Kather, Technical University of Hamburg, Germany.

10.10 to 10.30 Break

Session 6- Advance Oxy-Combustion Concept, Chair; Nysakala y Nysakala

10.30 to 10.50 Development in Chemical Looping Combustion; Tobias Mattisson, Chalmers University, Sweden.
10.50 to 11.10 CLC R&D efforts of Alstom; Herb Andrus, Alstom Power Inc., USA
11.10 to 11.30 Fixed Bed Membrane Assisted CLC; Sander Noorman, University of Twente, The Netherlands.

11.30 to 12.00 Lunch

Session 7- Panel Discussion – Large Scale Oxy-Combustion Demonstration Project ; Chair Sho Kobayashi

1245 – 1515 Coal Based Oxy-Fuel System Evaluation and Combustor Development
Leonard Devanna, Clean Energy System, USA
R&D Objectives of the Lacq Oxy-Boiler Retrotit Project: Development for Oxy-Combustion of Crude Oil, Transportation and Storage of CO_2 in Depleted Gas Reservoir
Nicolas Aimnard, Total, France
Project Overview of the SaskPower's 300MWe Oxy-Combustion Demonstration Power Plant:
Bob Stobbs, SaskPower, Canada
Status of Calide-A $30MW_e$ Demonstration Project
Chris Spero, CS Energy, Australia
Status of Schwarze Pumpe 30MW, Pilot Plant Project
Lars Strömberg, Vattenfall AB, Sweden
Jupiter Oxygen Projects Moving Oxy-Fuel Forward – Overview to their Large Scale Demo Project.Brian Patrick, Jupiter Oxygen, USA

Closing Session-Wrapping up and Future Activities

IEA GREENHOUSE GAS R&D PROGRAMME
Stoke Orchard Cheltenham Gloucestershire UK GL52 7RZ
Tel: +44 (0)1242 680753 Fax: +44 (0)1242 680758 e-mail: stanley@ieaghg.org

2nd Workshop

International Oxy-Combustion Research Network

Hilton Garden Inn
555 Corporate Drive
Windsor, CT, 06095

25th and 26th January 2007

LIST OF PARTICIPANTS

No.	Surname	First Name	Company	Country
1	AIMARD	Nicolas	Total E&P	France
2	Andersson	Klas	Chalmers University	Sweden
3	Axelbaum	RIchard	Washington University in Saint Louis	USA
4	Beers	Janos	Massachusetts Institute of Technology	USA
5	Biede	Ole	Vattenfall A/S – Thermal Power	Denmark
6	Bonaquist	Dante	Praxair	USA
7	Burböck	Martin	EVN AG	Austria
8	Choi	Sangmin	Korea Advanced Institute of Science and Technology	S. Korea
9	Cortés-Galeano	Vicente	School of Engineering, Sevilla University	Spain
10	Craigen	Jim	ACARP	Australia
11	Davison	John	IEA Greenhouse Gas R&D Programme	UK
12	Devanna	Leonard	Clean Energy Systems	USA
13	Ditaranto	Mario	SINTEF Energy Research	Norway
14	Doctor	Richard	Argonne National Laboratory	USA
15	Eddings	Eric	University of Utah	USA
16	Eriksson	Karin	Vattenfall R&D	Sweden
17	Eriksson	Timo	Lappeenranta University of Technology / FWEOy	Finland
18	Farzan	Hamid	The Babcock & Wilcox Company (B&W)	USA
19	Fogash	Kevin	Air Products and Chemicals, Inc.	USA
20	Fout	Timothy	National Energy Technology Laboratory	USA
21	Gale	Thomas	Southern Research Institute	USA
22	Gibbins	Jonathan	Imperial College London	UK
23	Goh	Ben	E.ON UK plc	UK
24	Hack	Horst	Foster Wheeler North America Corp.	USA
25	Heins	Klaus	University of Stuttgart	Germany
26	Hofstad	Karina Heitnes	Statoil ASA	Norway
27	Hotta	Arto	Foster Wheeler Power Group Europe	Finland
28	Hyppänen	Timo	Lappeenranta University of Technology	Finland
29	Iyer	Raj	The BOC Group Inc. (A member of the Linde Group)	USA
30	Johnsson	Filip	Chalmers University	Sweden
31	Jones	Morgan	First Energy Corp.	USA
32	Kather	Alfons	Hamburg University of Technology	Germany
33	Kim	Jong Soo	Korea Institute of Science and Technology	S. Korea
34	Kobayashi	Sho	Praxair	USA
35	Krishnamurthy	Krish R.	The BOC Group, Inc. (A member of The Linde Group)	USA
36	Lebas	Etienne	IFP	France
37	Li	Xinxin	Columbia University	USA
38	Lindgren	Goeran	Vattenfall R&D AB	Sweden
39	Maier	Joerg	University of Stuttgart / IVD	Germany
40	Mattisson	Tobias	Chalmers University	Sweden

No.	Surname	First Name	Company	Country
41	McCauley	Kevin	The Babcock & Wilcox Company (B&W)	USA
42	Misawa	Nobuhiro	J-POWER	Japan
43	Mitchell	Stuart	Doosan Babcock Energy Limited	UK
44	Nicolas	Perrin	Air Liquide	USA
45	Noorman	Sander	University of Twente	The Netherlands
46	Ochs	Thomas	USDOE - National Energy Technology Laboratory	USA
47	Panesar	Ragi	Doosan Babcock Energy limited	UK
48	Patrick	Brian	Jupiter Oxygen	USA
49	Peridas	George	Natural Resource Defence Council	USA
50	Prebende	Claude	TOTAL	France
51	Roiha	Kimmo	Technical Research Centre of Finland	Finland
52	Rossi	Nicola	ENEL Spa	Italy
53	Santos	Stanley	IEA Greenhouse Gas R&D Programme	UK
54	Sarofim	Adel	University of Utah	USA
55	Seltzer	Andrew	Foster Wheeler North America	USA
56	Shaddix	Christopher	Sandia National Laboratory	USA
57	Shah	Minish	Praxair, Inc.	USA
58	Sjoberg	Charles	AES NY	USA
59	Spero	Chris	CS Energy Ltd.	Australia
60	Stobbs	Bob	SaskPower	Canada
61	Strömberg	Lars	Vattenfall AB	Sweden
62	Topper	John	IEA Greenhouse Gas R&D Programme	UK
63	Tranier	Jean-Pierre	Air Liquide	France
64	Varagani	Rajani	Air Liquide	USA
65	Victor	Richard	Praxair Inc.	USA
66	Waining	Barry	IHI Engineering Australia Pty. Ltd.	Australia
67	Wall	Terry	University of Newcastle	Australia
68	Wendt	Jost	University of Utah / Reaction Engineering	USA
69	Wheeldon	John	EPRI	USA
70	White	Vince	Air Products PLC	UK
71	Whitehouse	Michael	RWE NPower PLC	UK
72	Yamada	Toshihiko	Ishikawajima-Harima Heavy Industries Co. Ltd. (IHI)	Japan
73	Zanganeh	Kourosh	CANMET, Natural Resources Canada	Canada
		Participants from Alstom		
1	Andrus	Herb	ALSTOM Power Inc.	USA
2	Bowles	Donna	ALSTOM Power Inc.	USA
3	Chamberland	Ray	ALSTOM Power Inc.	USA
4	Darling	Scott	ALSTOM Power Inc.	USA
5	Ericson	Amy	ALSTOM Power Inc.	USA
6	Fiveland	Woody	ALSTOM Power Inc.	USA
7	Gedeon	Elias	ALSTOM Power Inc.	USA
8	Jukkola	Glenn	ALSTOM Power Inc.	USA
9	Kawa	Peter	ALSTOM Power Inc.	USA
10	Kluger	Frank	Alstom Power Boiler GmbH	Germany
11	Liljadahl	Greg	ALSTOM Power Inc.	USA
12	Lillestollen	Tom	ALSTOM Power Inc.	USA
13	MacDonald	Derek	ALSTOM Power Inc.	USA
14	Marion	John	ALSTOM Power Inc.	USA
15	Mohn	Nancy	ALSTOM Power Inc.	USA
16	Nskala	Nskala	ALSTOM Power Inc.	USA
17	Paelinck	Philippe	ALSTOM Power Inc.	France
18	Pfeffer	Allen	ALSTOM Power Inc.	USA
19	Suraniti	Silvestre	ALSTOM Power Boiler	France

Welcome Address

John Marion

IEAGHG International Oxy-Combustion Network
Windsor, CT, USA
January 24-26, 2007

Who is ALSTOM ?

ALSTOM

N°2 worldwide in rail transport

Alstom makes 1 metro in 4 and 1 tram in 3

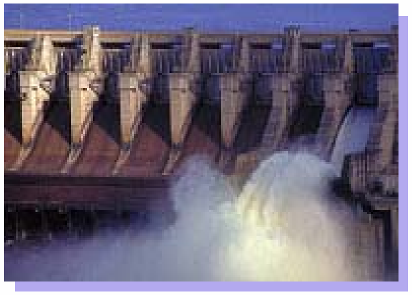
N°1 worldwide
in high speed
and very high speed

N°2 worldwide
in urban transport
(metro and trams)

N°3 worldwide in electricity production

Alstom supplies 27% of global capacity for the production of electricity

N°1 worldwide
in turnkey
power plants



N°1 worldwide
in hydroelectric

N°1 worldwide
in environmental
control systems

N°1 worldwide
in services for
electricity utilities

A global leader for Power Generation and Rail Transport

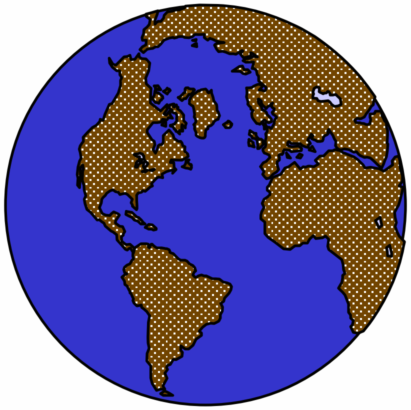
What’s ALSTOM doing about CO_2?

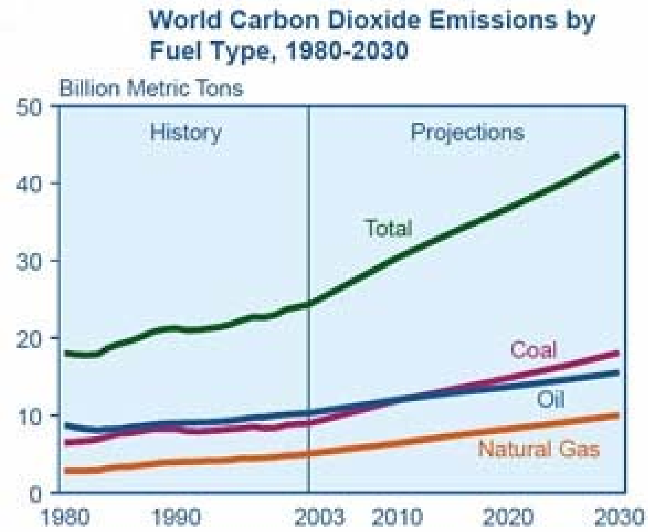
- ALSTOM is a world-leading supplier of power generation equipment, turnkey power plants and services, and is an industry leader in providing modern, high-efficiency clean power generation equipment and energy solutions
- ALSTOM believes that providing a diverse mix of technologies for power generation is a critical element in providing affordable, reliable, and environmentally sound energy.
- There is no single, all-encompassing, long-term technological option for greenhouse gas mitigation; rather, there will be a variety of options that will be needed.
- ALSTOM continues to focus its major R&D investments in the demonstration of cost effective and practical power generation systems aimed at both improved efficiency and emissions control (including capture). Through these principles, ALSTOM is committed to the continuous improvement of its technology portfolio in order to meet the present and future needs of its customers.

ALSTOM

CO_2 Mitigation Options - for Power

- **Conservation**
- **Increase efficiency**
  - **[of fossil fuel energy conversion]**
- **Fuel Switch**
  - **nuclear**
  - **renewables**
  - **natural gas**
- **CO_2 Sequestration**
  - **Capture**
  - **Sequestration**





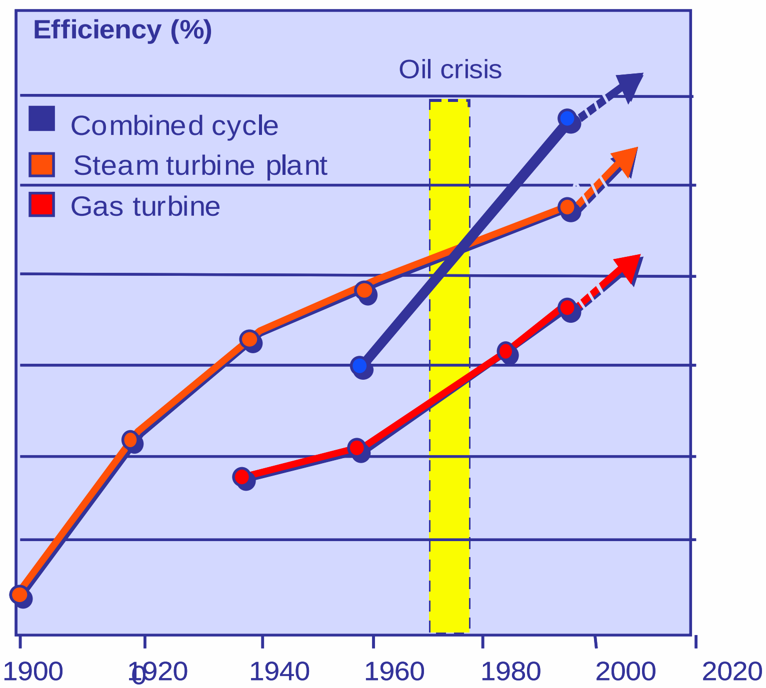
EIA Energy Outlook 2006

Fossil Fuel use is projected to increase

CO_2 Mitigation Options - for Power

- **Conservation**
- **Increase efficiency**

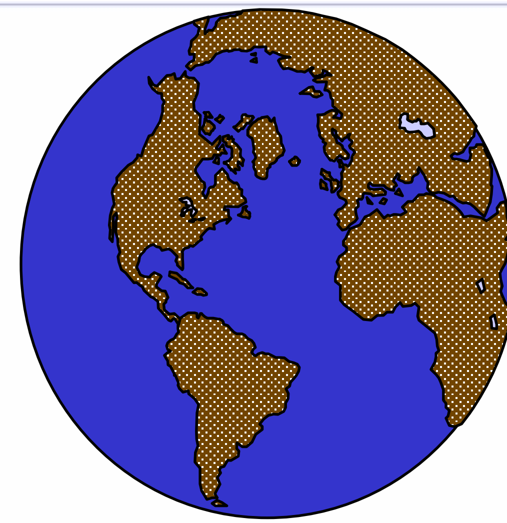
  [of fossil fuel energy conversion]



- **Reduces emissions**
- **Reduces CO2**
- **Saves limited fuels resources**

Efficiency improvement is a "no regrets" strategy we can implement today!

CO_2 Mitigation Options - for Power



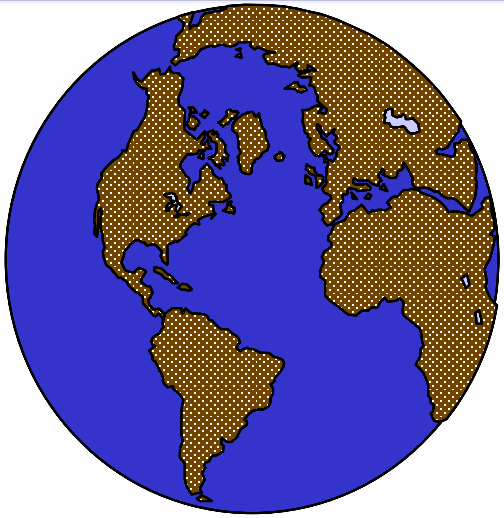
- **Conservation**
- **Increase efficiency**
  - **[of fossil fuel energy conversion]**
- **Fuel Switch**
  - **nuclear**
  - **renewables**
  - **natural gas**

- **CO_2 Sequestration**
  - **Capture**
  - **Sequestration**

Needed in the long run if we continue to use fossil fuels and commit to CO2 emissions stabilization

ALSTOM

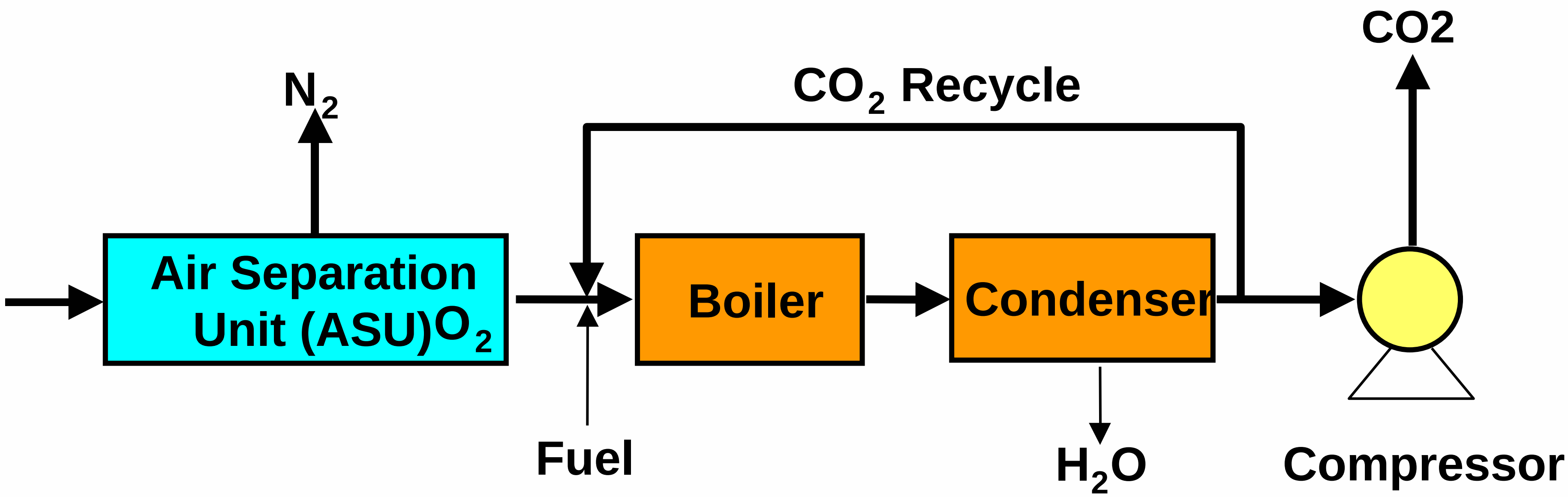
CO_2 Capture Approaches - for Power

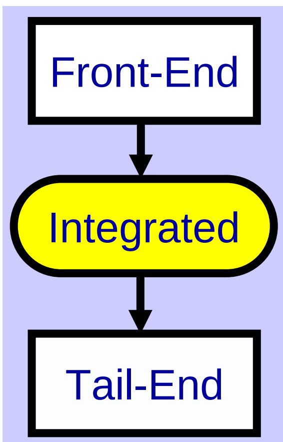


- **Post Capture**
  - **Adsorption**
  - **Absorption**
  - **Hydrate based**
  - **Cryogenics / Refrigeration based**
- **Oxy-fuel Firing**
  - **external oxygen supply**
  - **integrated membrane-based**
  - **oxygen carriers**
- **Decarbonization**
  - **reforming (fuel decarbonization)**
  - **carbonate reactions (combustion decarbonization)**

Innovative options continue to emerge and develop

Oxy-fuel Firing



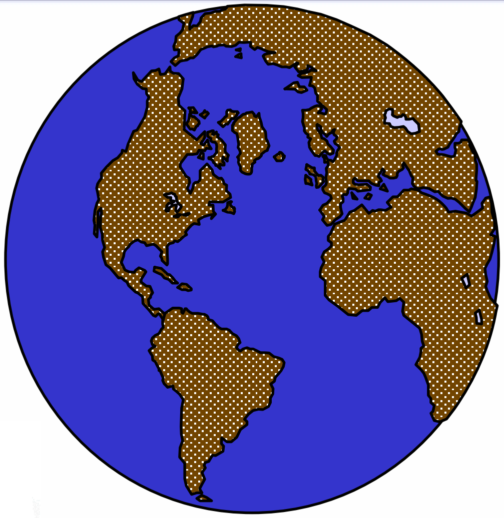


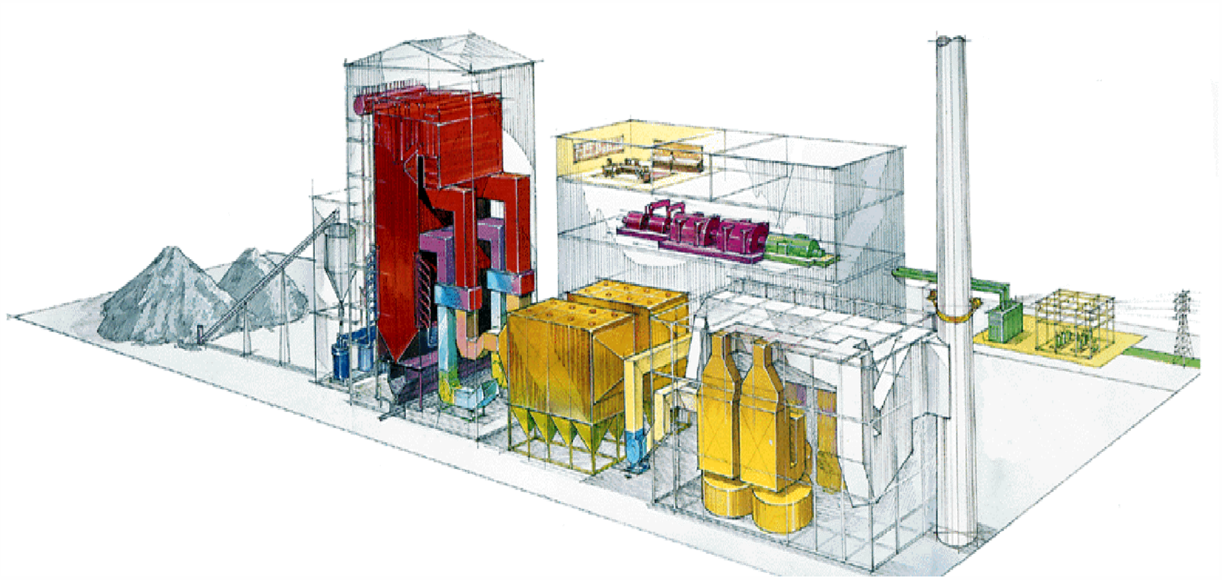
Oxygen Firing to produce concentrated CO2 stream

ALSTOM

Oxy-fuel Firing

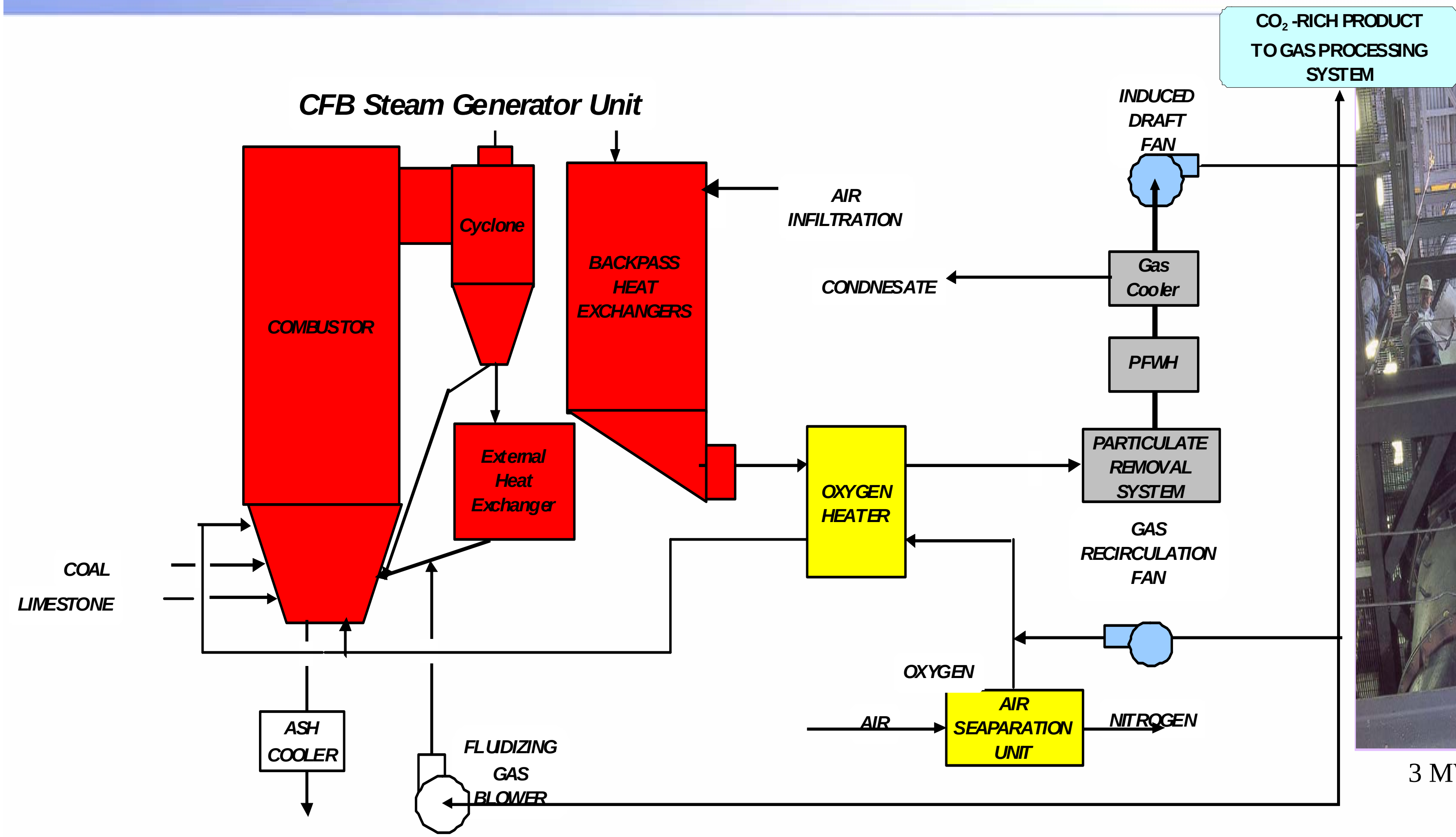
- Complimentary with current boiler and steam power plant technology, including efforts towards ultra-supercritical conditions, and environmental control developments
- Applicable for new and retrofit plants

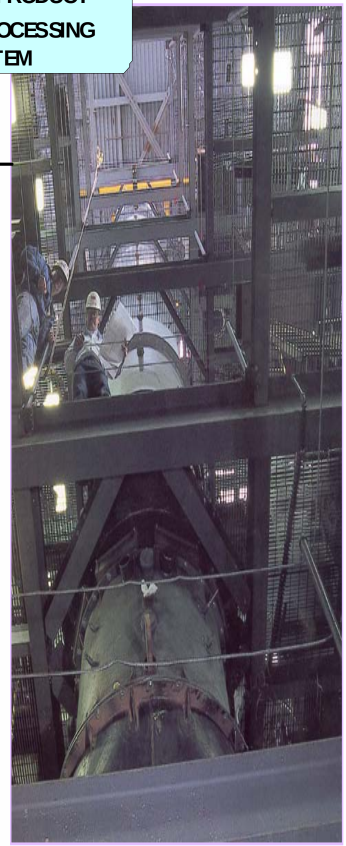




Evolutionary development for coal power

Oxy-CFB





3 MWt pilot CFB

Reduced recycle FGR and resultant smaller boiler & APC

ALSTOM

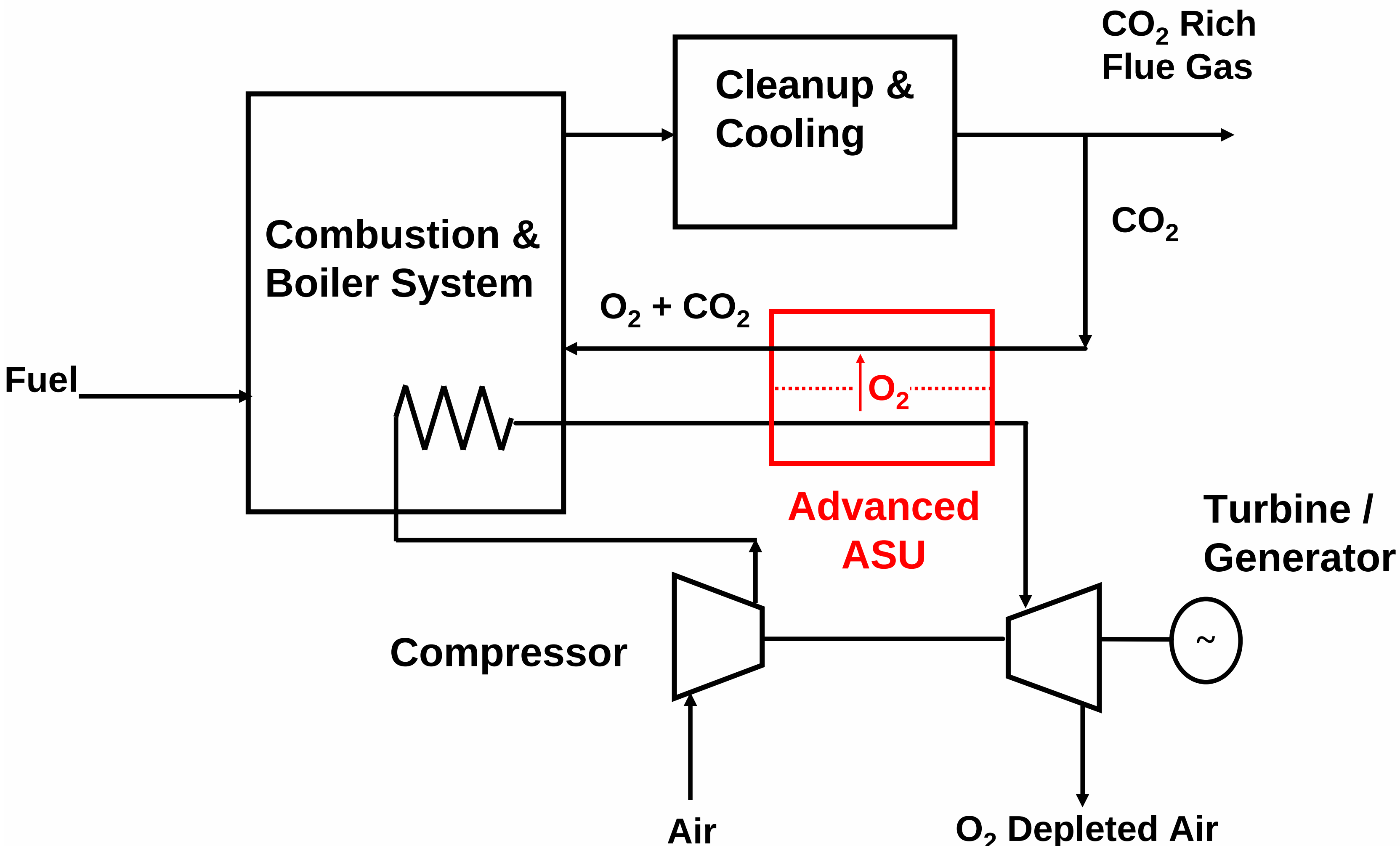
30 MWth Oxy-fuel PF Pilot Plant – Vattenfall

Location of pilot plant in the Industrial Park Schwarze Pumpe

Development Steps	Scale-up Factor	Objective	Com	Partners
Laboratory Tests 10 / 55 kWth		Fundamentals of oxyfuel combustion	2004 2005	Universities (Stuttgart, Chalmers, Dresden) Vattenfall, ALSTOM..
Test Plant 500 kWth	1:50	Fundamentals of oxyfuel combustion with flue gas recirculation	2005	CEBra, BTU Cottbus, Vattenfall, ALSTOM
Pilot Plant 30 MWth	1:60	Test of the oxyfuel process chain	2008	Vattenfall..., ALSTOM, others
Demo Plant 600 MWth	1:20	Realisation with CO2 sequestration,	2015	
Commercial Plant approx. 1000 MWel	approx. 4-5		2020	

First of a kind large demonstration of Oxy-PF Power Plant

Oxy-Fuel Power Plant with Advanced O_2 Production Technology



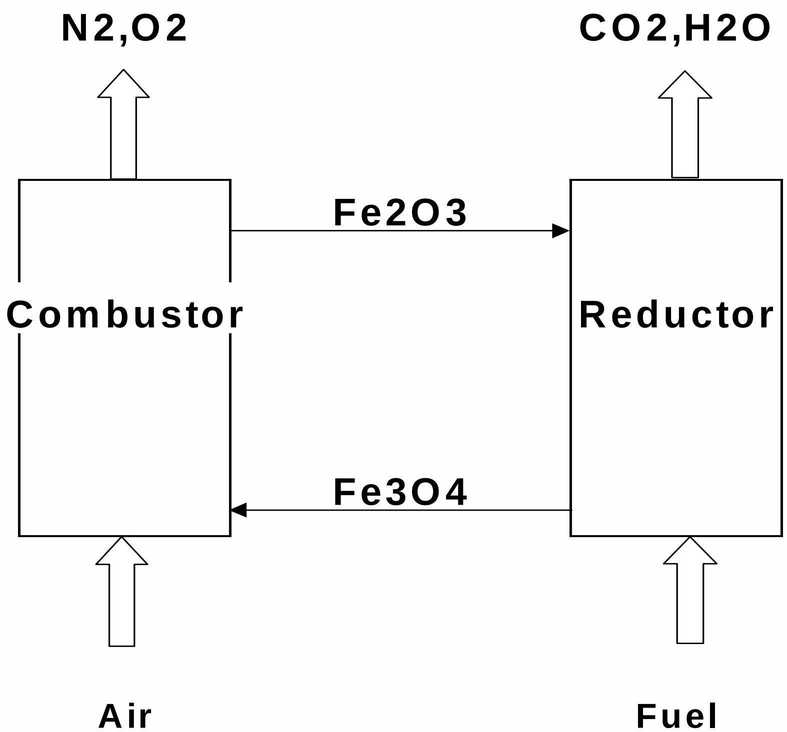
Breakthroughs will improve oxy-firing performance and economics

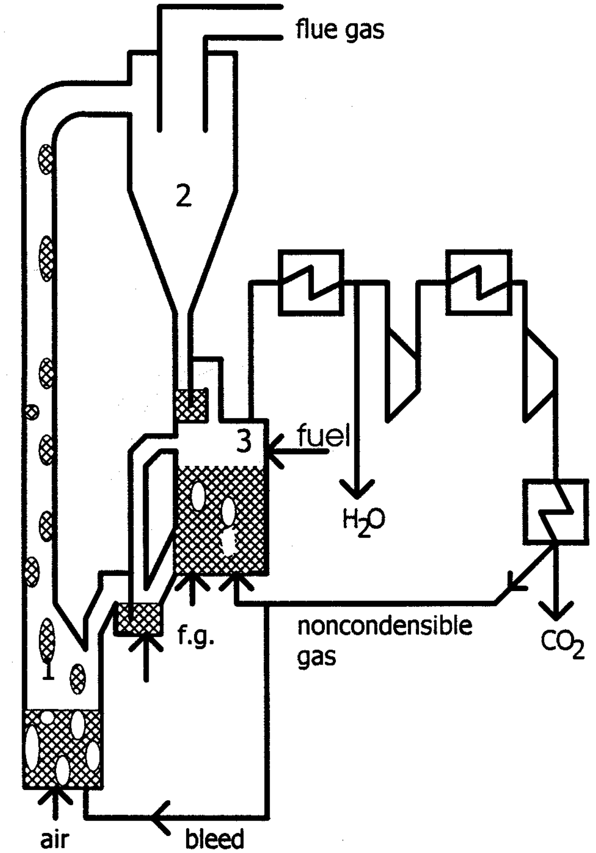
IEAGHG International Oxy-Combustion Network
J.Marion- 24-26, January 2007

ALSTOM

Chemical Looping

Metal oxides oxygen carriers – a type of oxy-fuel firing – shown here in connected CFB's



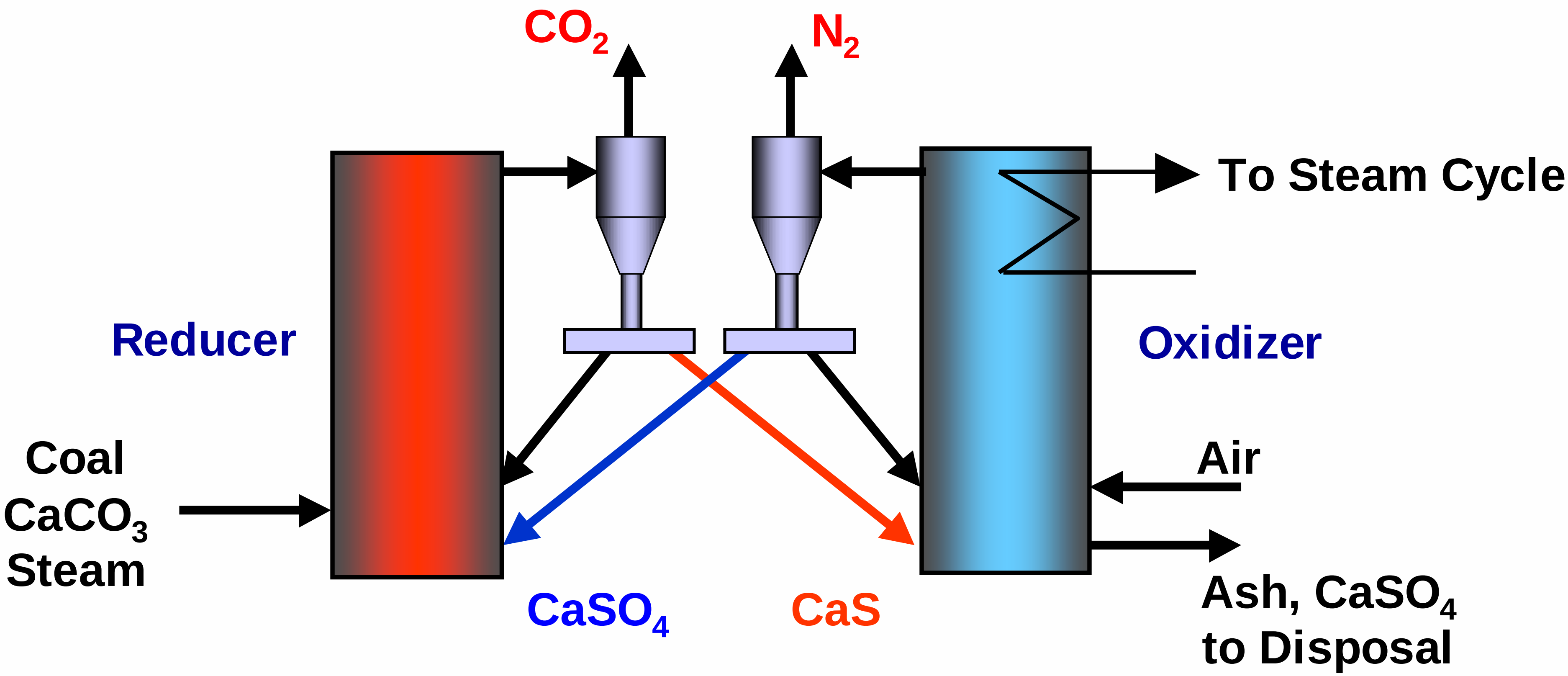


Chalmers U., ALSTOM, others

Chemical Looping is a potential breakthrough technology

Chemical Looping

CaS - CaSO4 loop in CFB reactors



Combustion with CO2 Capture

Calcium-based oxygen carrier process is suited to coal

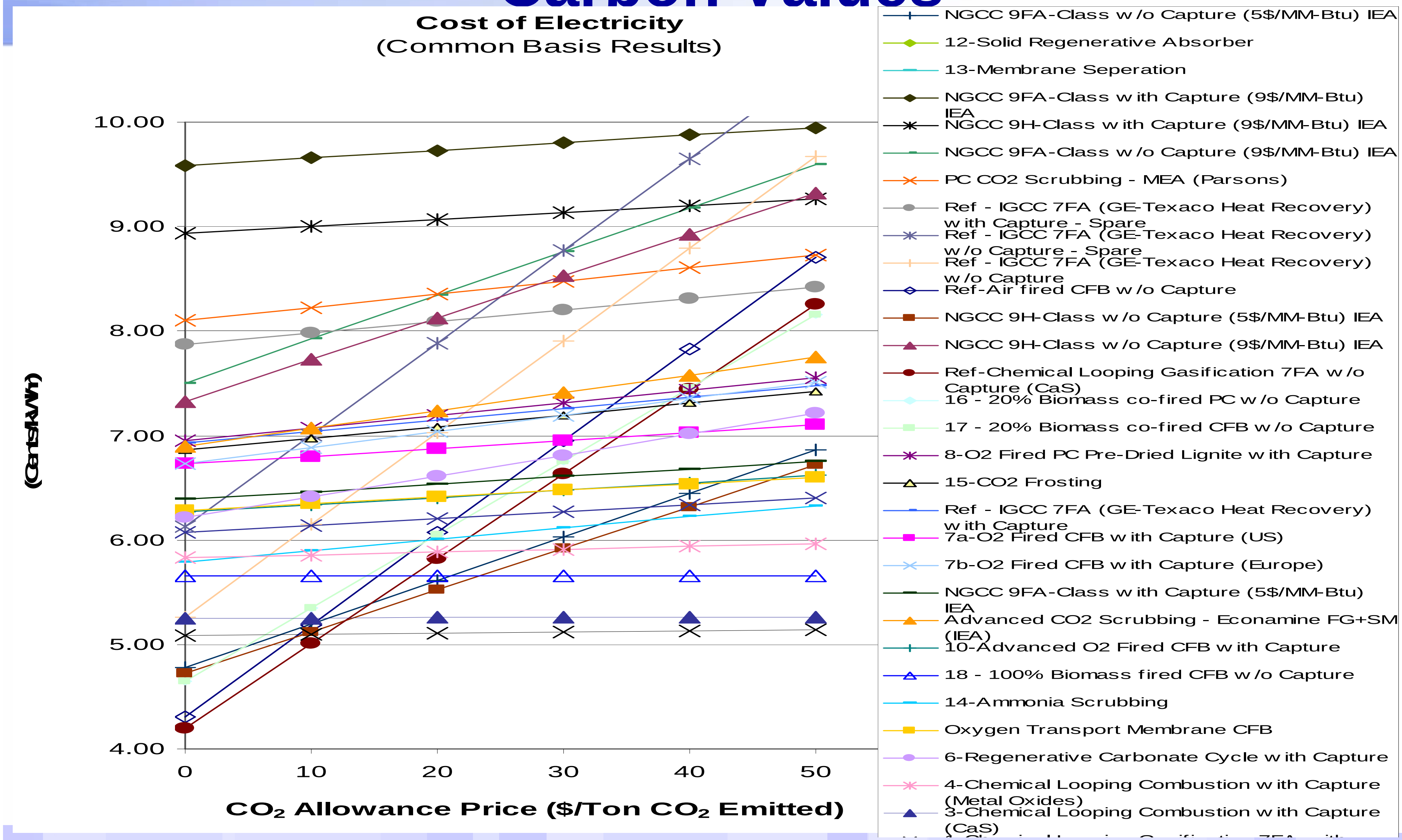
Economics of Electricity Production with Carbon Values

Economic Assumptions

• Coal Cost	1.50 ($/MM-Btu)
• Natural Gas Cost	Range: 5.0 - 9.0 ($/MM-Btu)
•Capacity Factor	80% - 7,008 (hrs/yr)
• Performance (thermal efficiency)	Taken from referenced studies
• Investment Costs ($/kW)	Taken from referenced studies
• Annual Capital Charge Rate	13.5% of investment cost
• Operating & Maintenance Costs	Taken from referenced studies
•CO_2 allowance price	Range: 0-50 ($/Ton of CO_2)

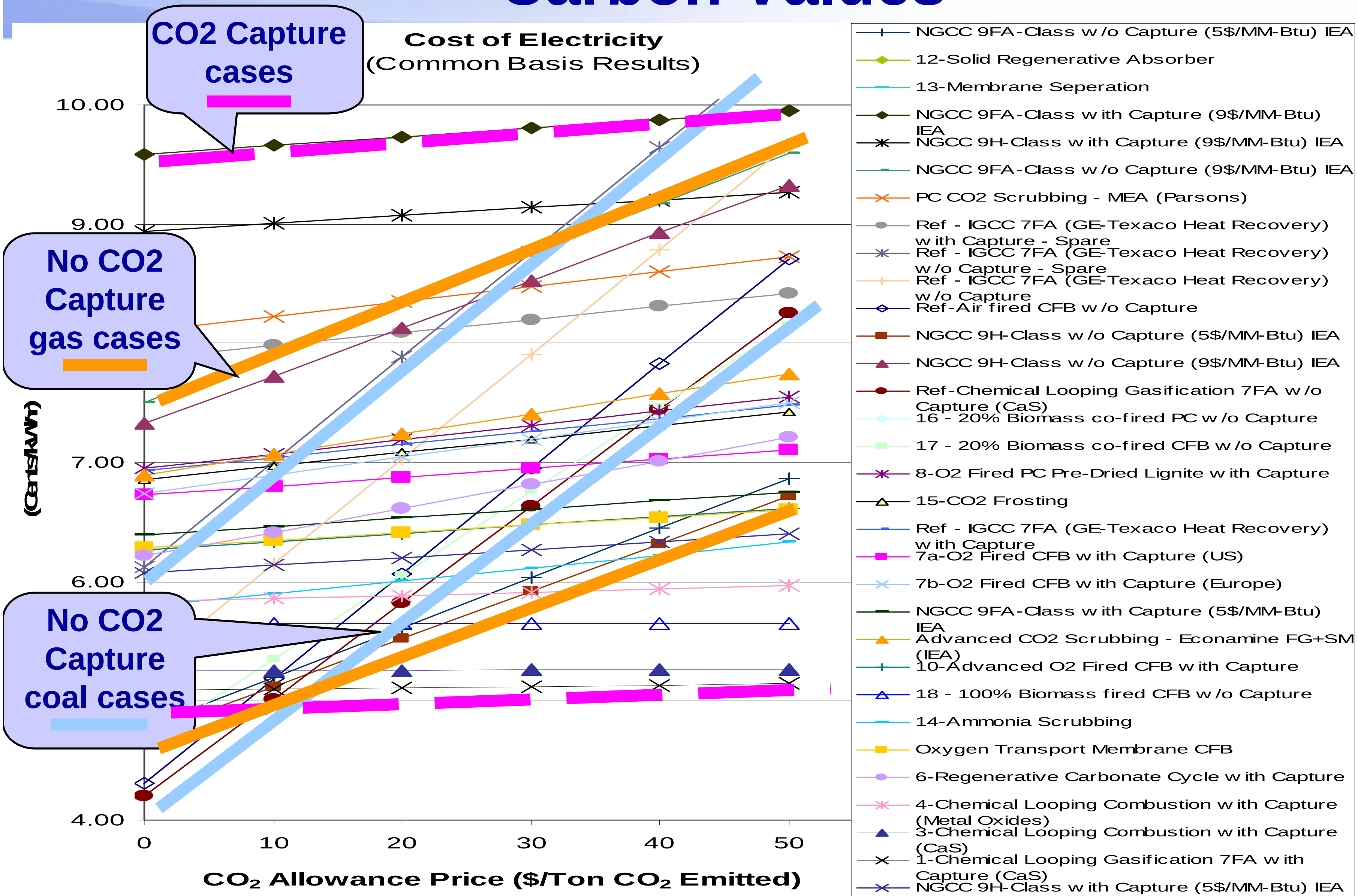
COE vs CO_2 Value

Economics of Electricity Production with Carbon Values



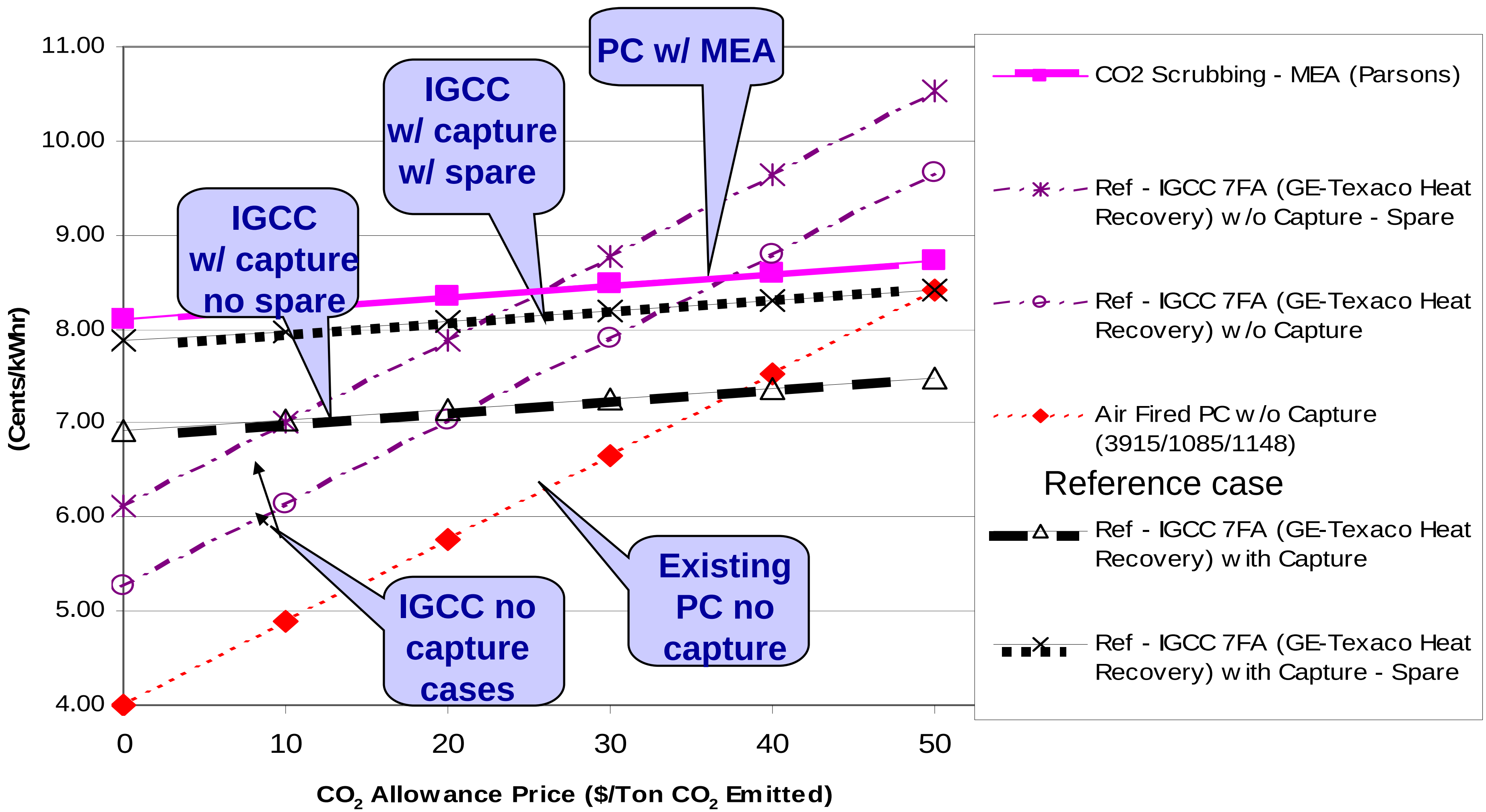
Many cases – look at Dispatch then COE vs CO2 values

Economics of Electricity Production with Carbon Values



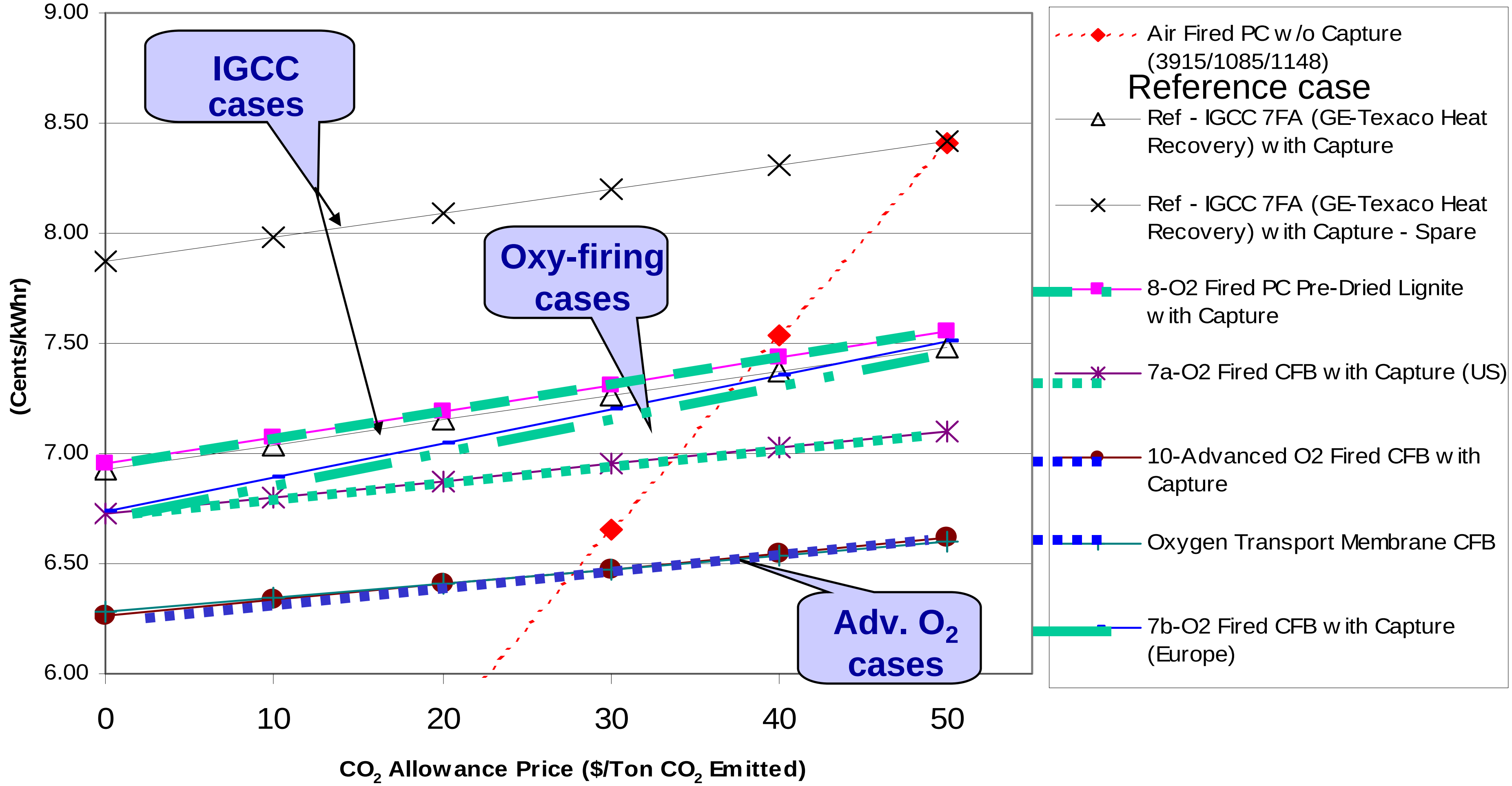
ALSTOM

CO_2 Capture in Power Plants



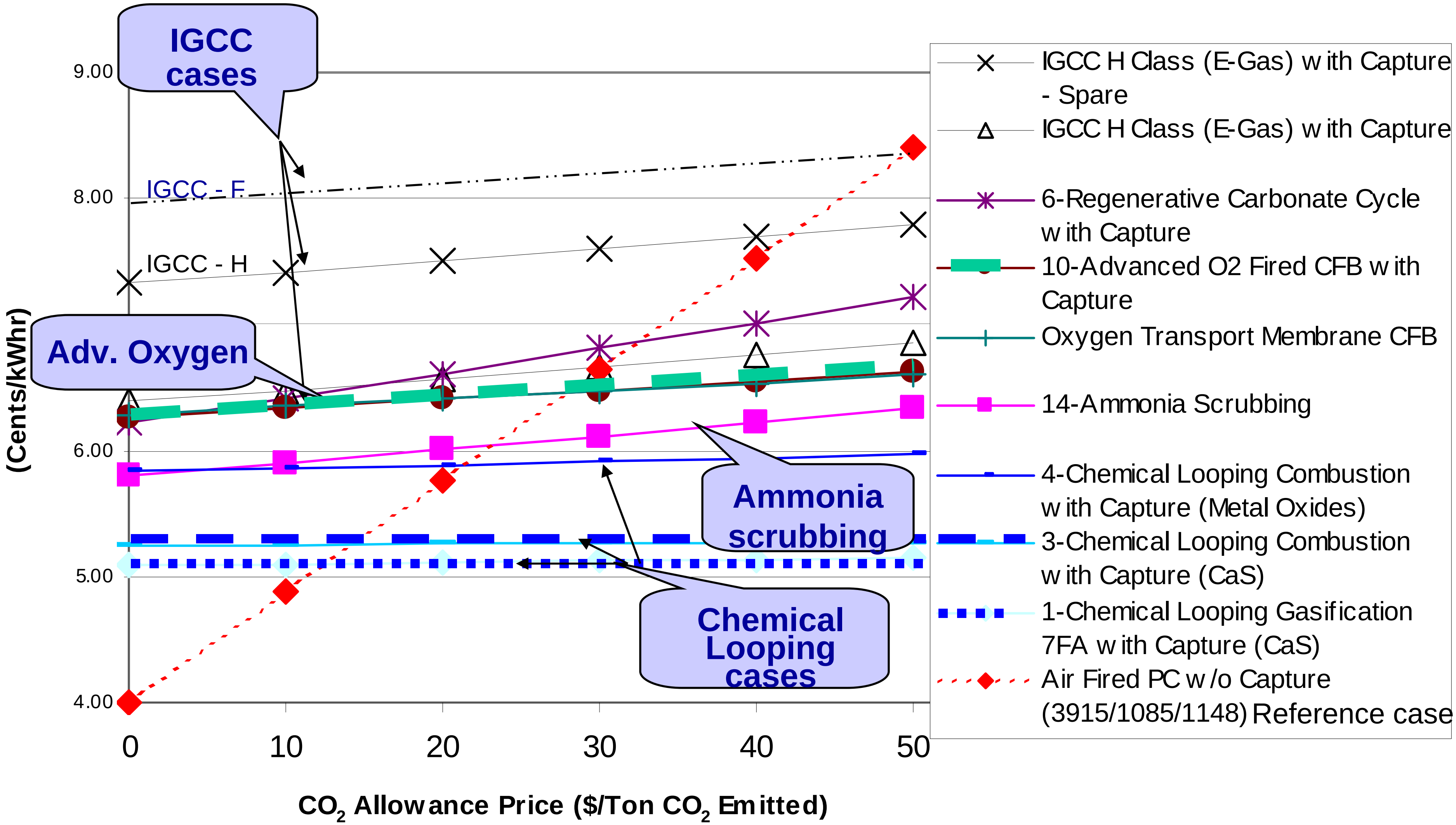
Incomplete picture of Capture Options

CO_2 Capture in Power Plants



Oxy-firing with conventional or advanced O2 generally lower COE than IGCC

CO_2 Capture in Power Plants



Advanced concepts have great potential

Conclusions

- **New coal fired power plants shall be designed for highest efficiency to minimize CO2 + other emissions**
- **Several technologies for CO2 capture are currently available, several are actively being developed, and many more are emerging**
- **Including --- Oxy-fuel firing for CO2 capture for Combustion-based Power**
- **Cost Attractive Options are needed and should actively supported, particularly:**
  - **Breakthroughs (example: chemical looping & adv. oxygen)**
  - **Retrofitable (example: oxy-firing and ammonia scrubbing)**
- **There is no single technology answer**
- **Our workshop will provide a comprehensive update of Oxy-fuel firing development and the challenges ahead.**

ALSTOM

www.alstom.com

International Network for Oxy-Combustion with CO_2 Capture

Introduction to 2nd Workshop

Windsor, CT, USA

by

John M. Topper

Managing Director

IEA Environmental Projects Ltd

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

Current Membership

ALSTOM * B&W * BG GROUP bp Chevron EniTecnologie e-on EPRI

ExxonMobil REPSOL YPF RWE * Schlumberger STATOIL TOTAL VATTENFALL

* *Formalities pending*

www.ieagreen.org.uk

International Network for Oxy-Combustion with CO2 Capture

- AIM: To establish a forum that will encourage practical work on oxy combustion based CO_2 capture.

- WHY CO-OPERATE?:
  - avoid duplication of effort
  - encourage development
  - minimise cost of participation
  - enhance technology credibility
  - reduce risks

1st Workshop

1st Workshop was hosted by Vattenfall at their Schwarze Pumpe Power station in Cottbus, Germany.

It was attended by 64 Participants from 17 Countries.

13 presentations were made covering topics ranging from modelling and laboratory studies through to demonstration plant build intentions

At this Meeting

- We have had to close registration list early because of the demand – over 85 people are attending (~20 persons in the waiting list)
- Excluding participants from Alstom Power, breakdown of participants shows that there are:
  - 33 participants from N America (44.6%);
  - 33 from Europe (44.6%);
  - 4 from Australia (5.4%);
  - 2 from Japan (2.7%); and
  - 2 from South Korea (2.7%)
- Participants from 16 different countries are present today
- Excellent networking

Today: Housekeeping Points

- Coffee breaks around 10.20 and 15.10
- Lunch, 12.20 followed by photos
- Afternoon session will finish at around 17.30 Dinner this evening in the 19.00 – Alstom to provide details.
- **ALL PRESENTERS ensure Stanley gets a copy of their presentation on data storage stick if you want it on the GHG website next week**
- Mobile phones off or on vibrating alert

Other Matters

- We are now looking for a host for our next meeting.
- If you would be interested to host the next workshop please approach IEAGHG team (myself, Stanley or John) to be considered.
- Planning to hold the workshop between March and April next year.
- Announcement will be made to everyone by the end of June 2007

Thanks to Alstom

- For local organisation
- And for Sponsoring the Dinner this evening.
- and for the facilities visit and welcome drink yesterday

Oxy-fuel Combustion: Progress and Remaining Issues

Adel F. Sarofim

University of Utah

Reaction Engineering International

2nd IEAGHG International Oxy-Combustion Workshop

Hilton Garden Inn, Windsor, CT

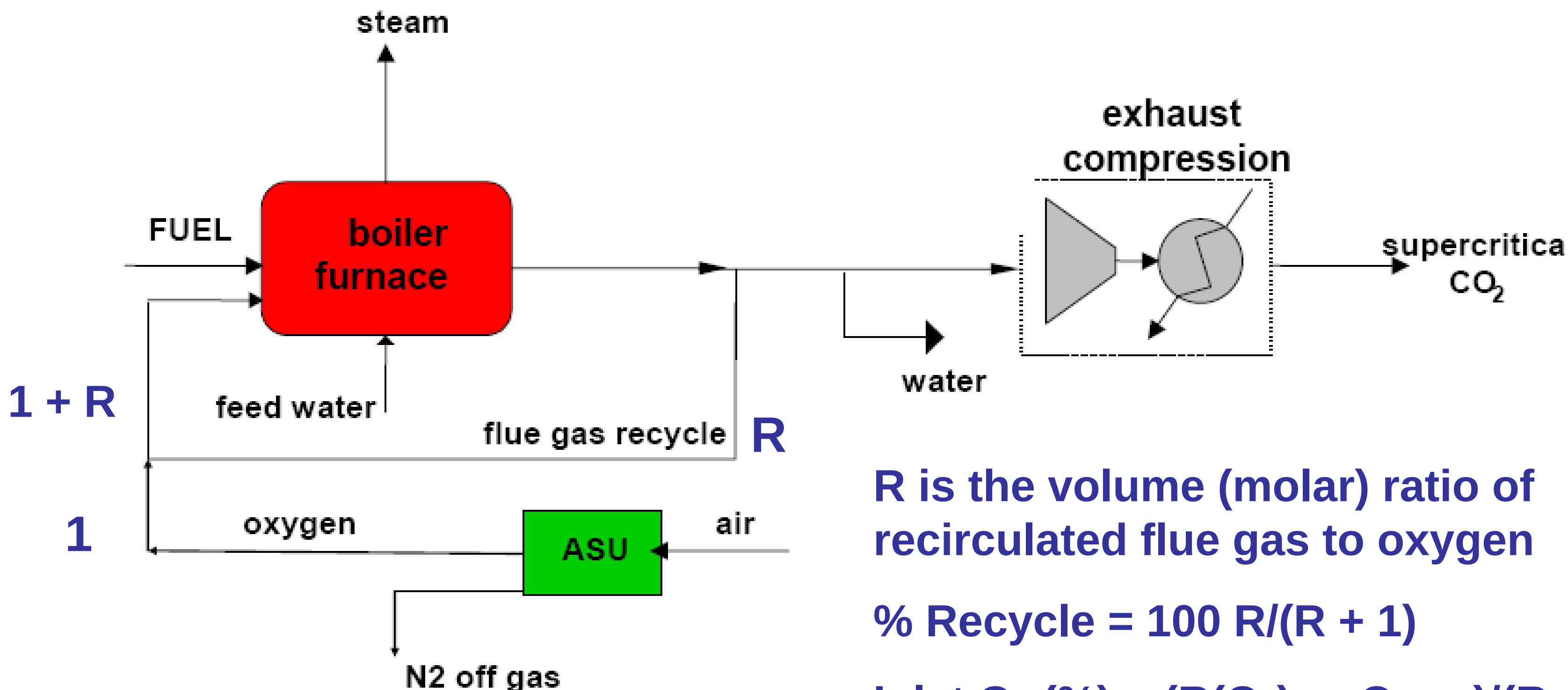
January 25-26, 2007

Acknowledgements

Rodney Allam, Milind Deo, Eric Eddings, Sho Kobayashi, Stanley Santos, Minish Shah, Lars Strömberg, Terry Wall, Jost Wendt, Vince White

Definition of Recirculation Ratio (adapted from Praxair, ’05)

The present manifestation of oxy-fuel combustion is to have oxygen mimic air by mixing 1 mole of oxygen with R moles of recirculated flue gases



R is the volume (molar) ratio of recirculated flue gas to oxygen

% Recycle = 100 R/(R + 1)

Inlet O_2 (%) = $(R(O_2)_e + O_{2,AS})/(R+1)$

= $100/(R+1)$ when $(O_2)_e = 0$ and

$O_{2,ASU}=100$

Heat Transfer

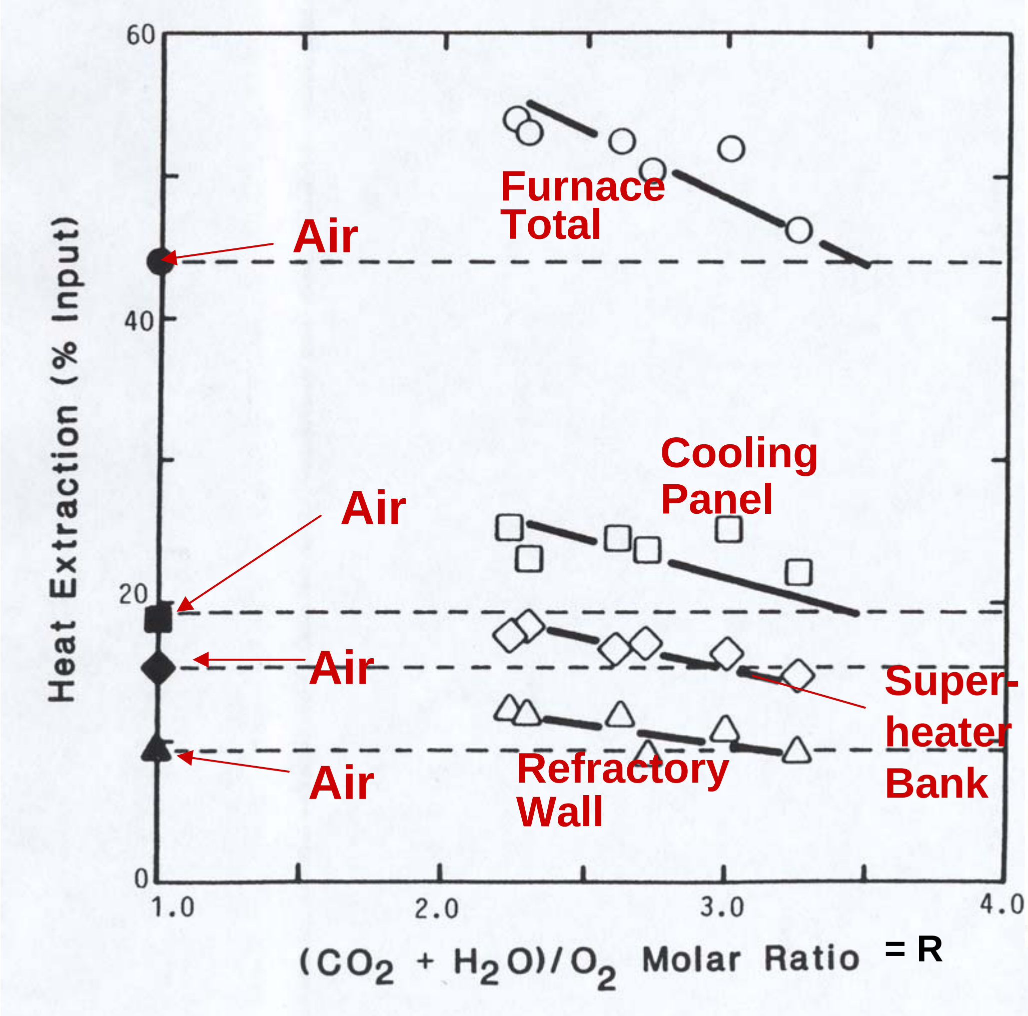
"For a boiler retrofit, what is the optimum recycled flue gas ratio where heat transfer profile could be similar to the air-fired system, and will this be dependent on the type of boiler and its configuration?"

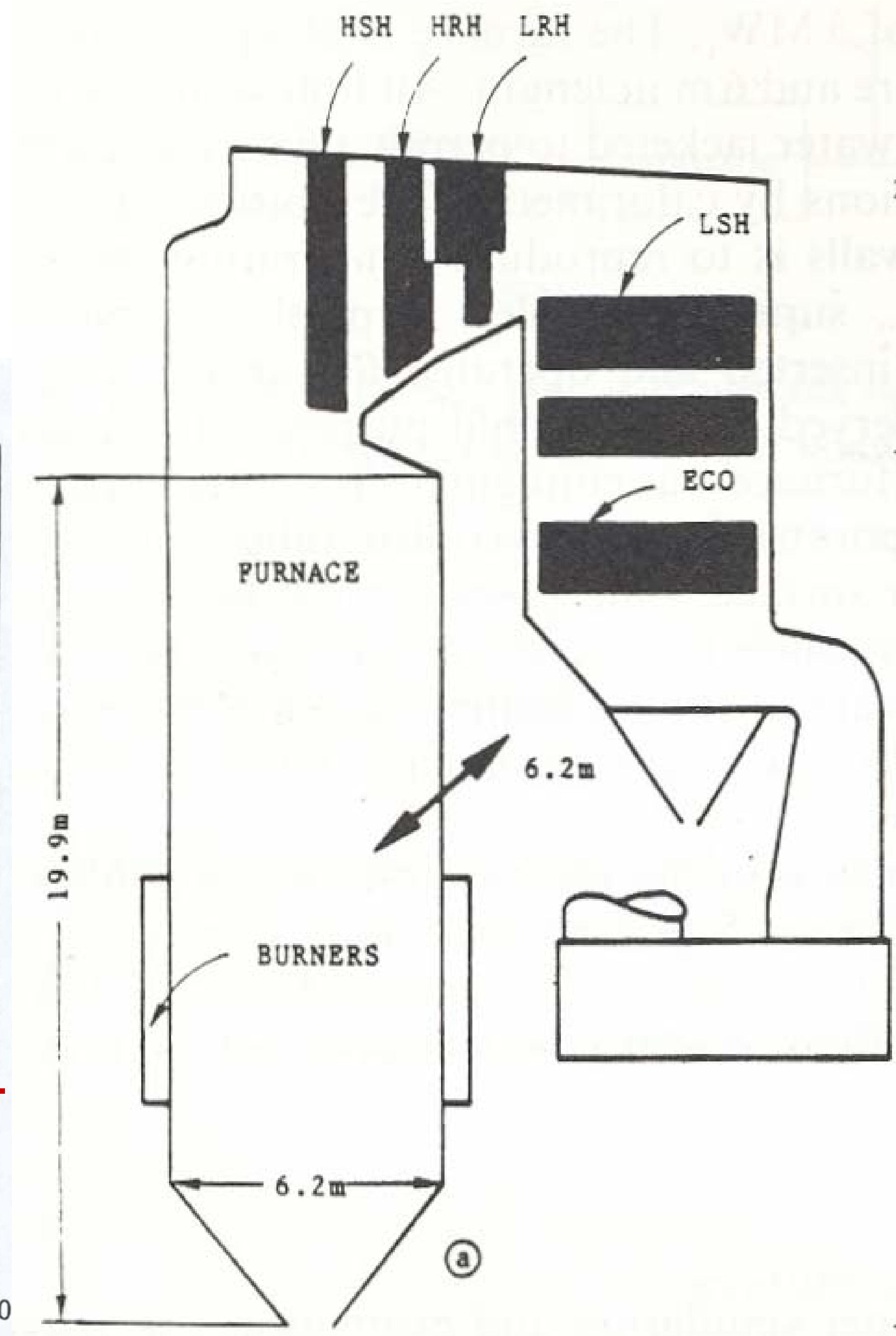
The ratio R of recirculated CO_2 to Oxygen is around 3 if heat flux for air combustion is to be matched

Case	$O_{2,\ eff}$	T_{AF} K	p_c	p_w	ε, T=1500 K L=15 m	q_{max}, kW/m^2
Air	21%	2302	0.16	0.089	0.51	812
O_2 R=1	51%	3176	0.64	0.34	0.68	3,946
O_2 R =2	35%	2330	0.64	0.34	0.68	1,140
O_2 R=3	27%	1891	0.64	0.34	0.68	496

The recycle ratio will depend upon furnace size, oxygen purity, coal type, temperature of recycle (Prof. Kather) and will be reduced by solid recycle in FBC (Alstom)

Zone method for a 50 MWe plant shows a match for the furnace at a value of ~ 3.3 (Payne et al., '89) Black Thunder Coal 10^7 Btu/hr with small local differences





Progress in our understanding of heat transfer

- The recycle ratio R is now determined as the value required to match the heat transfer for the air-fired furnace (not adiabatic flame temperature). R is predictable, increases with increasing gas emissivity (size of furnace), and is of the order 3. The value will be smaller for FBC where the recirculating solids can be used to control peak temperatures.
- The mean velocity of gases is reduced by the factor of (R+1)/4.76 ≅ 0.84. This will provide a longer residence time in the radiant section of furnace.
- The product of velocity and average heat capacity of the predominantly CO_2/H_2O mixture is greater than that of conventional combustion products so that the exit gas temperature for the O_2 firing is lower when the recycle ratios are selected to match the heat transfer in radiant chamber (Wall, 2007).
- The effect of lower velocity in the convective section is more than offset by lower kinematic viscosity for the oxy-combustion, so the Reynolds numbers and convective heat transfer coefficients will increase. The balance of heat transfer between the water cooled walls, radiant and reheat panels, and convection section will differ slightly between air and oxy-combustion but can be compensated for by either
  - Changes in operation (burner tilt, attemperation in superheater and reheater, …) for retrofit or
  - design changes for new units.
- Zone and CFD models (Vattenfall, Newcastle, IVD, Chalmers) are extremely valuable. However, the predictive capability is constrained by the uncertainty in the thermal resistance of the ash deposits, typically of the order of 1 $(m^2)(K)/Kw$, which is of the same magnitude as the gas to surface resistance for radiative heat transfer in the radiant section.

Emissions

“It has been reported that NO_x and SO_2 emission tend to reduce during oxy-firing conditions; unfortunately, the mechanisms behind these reductions have yet to be understood.”

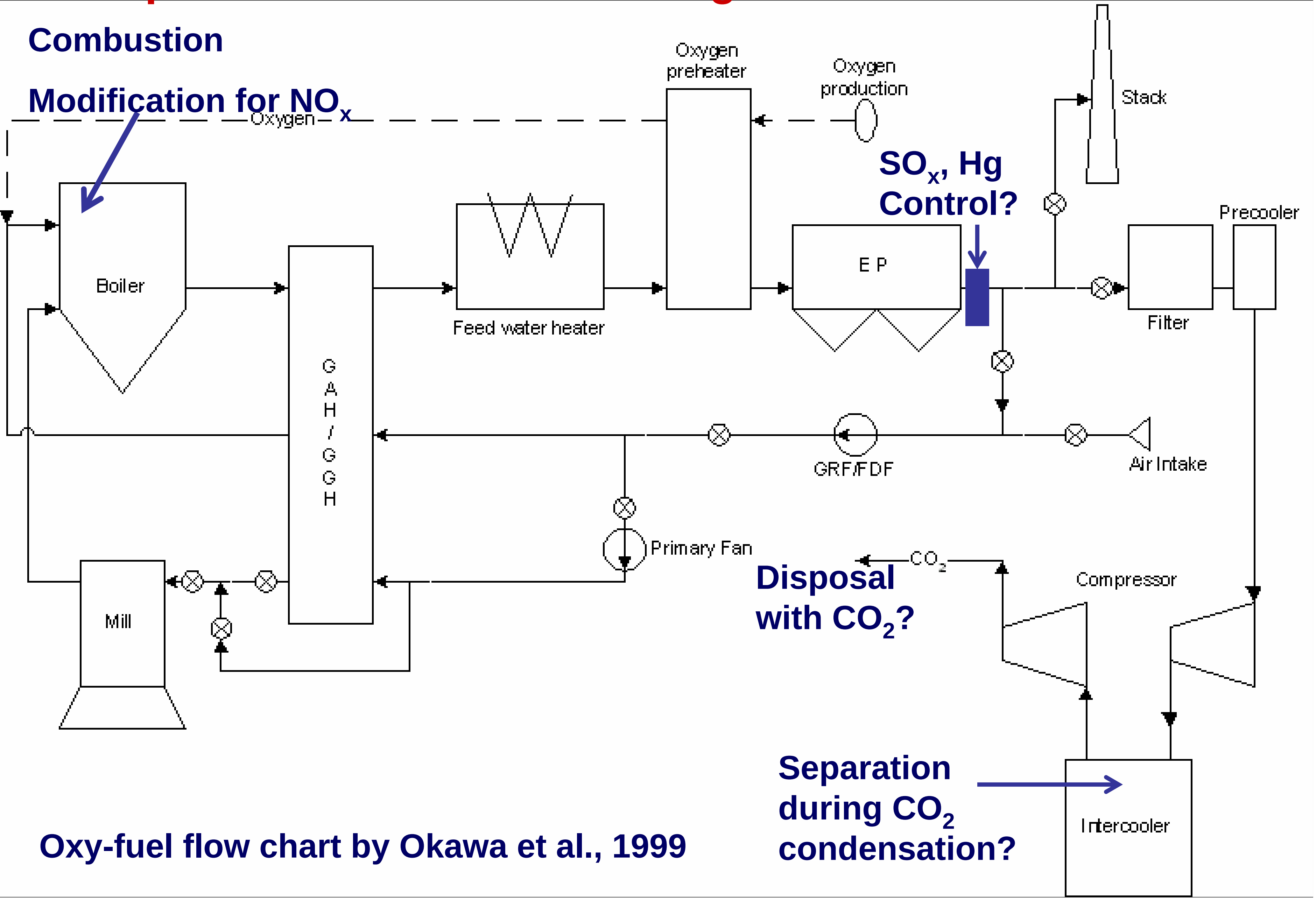
“What is the purity of CO_2 for transport and further storage?”

Gas compositions (omitting non-condensables) and volumes for bituminous coal ($CH_{1.1}O_{0.2}N_{0.017}S_{0.015}$) fired with air and oxygen

	Air Firing	Oxy-Firing
CO_2	17 % by volume	64%
H_2O	8.9%	34%
NO_x	2770xCR* ppm	10,700xCR* ppm
SO_x	2470 ppm	9400 ppm
Moles	1	0.26

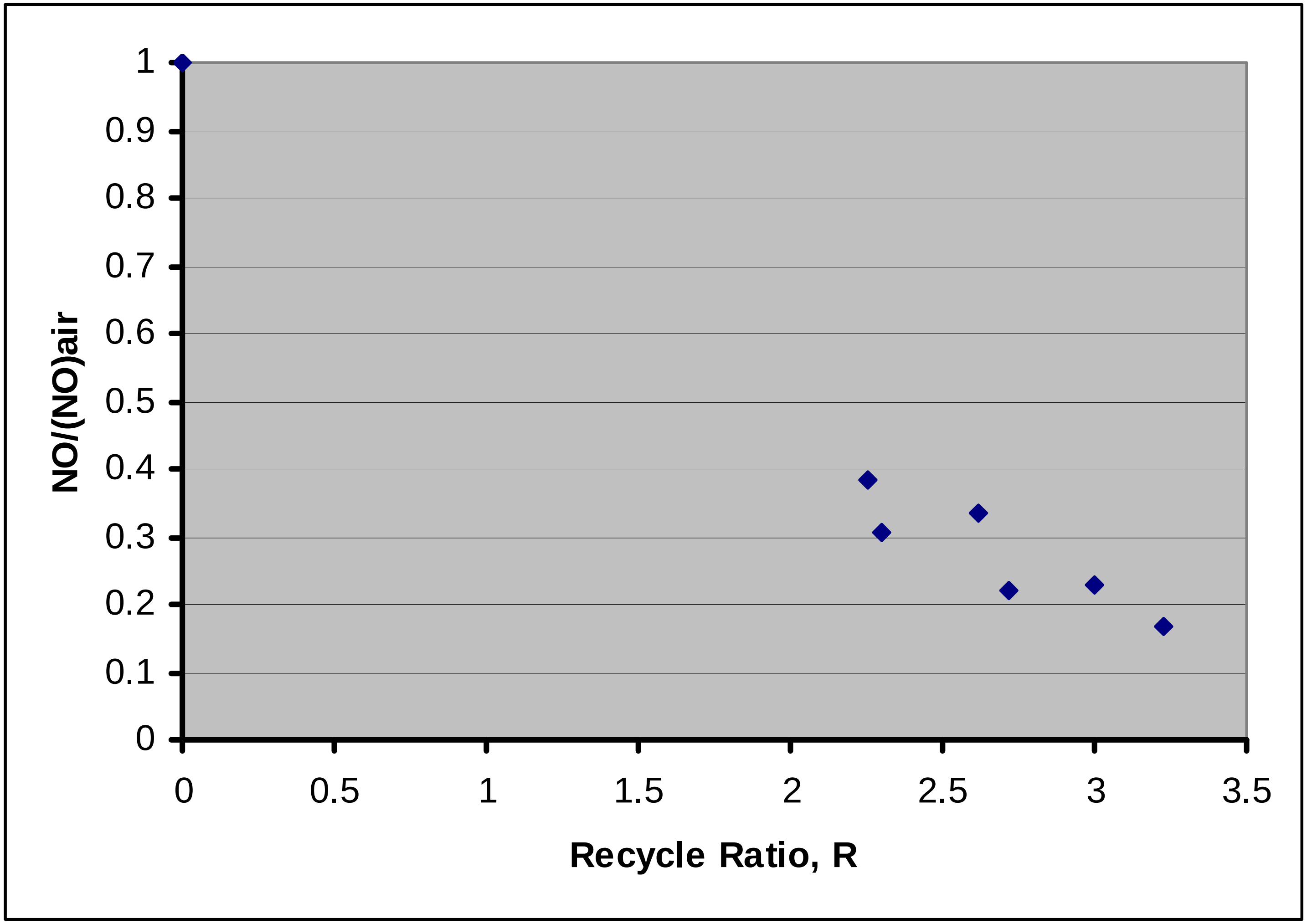
CR* = fractional conversion of coal nitrogen to NO_x

Options for Control of trace gas contaminants



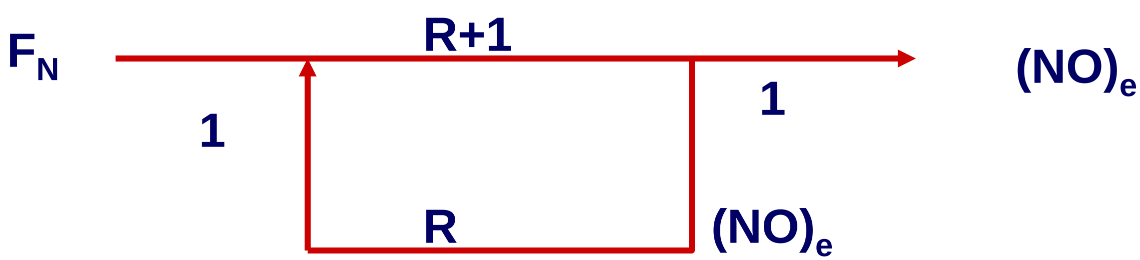
Oxy-fuel flow chart by Okawa et al., 1999

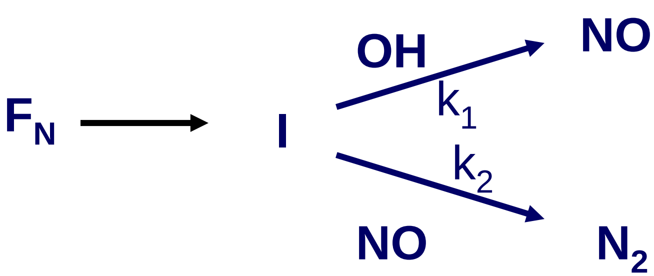
Major NO_x Reduction with Oxy-Combustion (Payne et al, 1989)



Reduction Consistent with 1. Reburning Due to Recirculation and 2. Decrease of Fuel Nitrogen Conversion with Increased NO Concentration

Simple Model (based on Okazaki, 2003)





$$\alpha = \frac{k_1 (I)(OH)}{k_1 (I)(OH) + k_2 (I)(NO)} = \frac{1}{1 + \frac{k_2 (NO)}{k_1 (OH)}}$$

$(R+1)(NO)_e = \alpha F_N + R(NO)_e (1 - \eta)$

$(NO)_e = \alpha F_N / \{R\eta + 1\}$

where α is fraction of fuel nitrogen converted to NO and η is fraction of NO destroyed by reburning

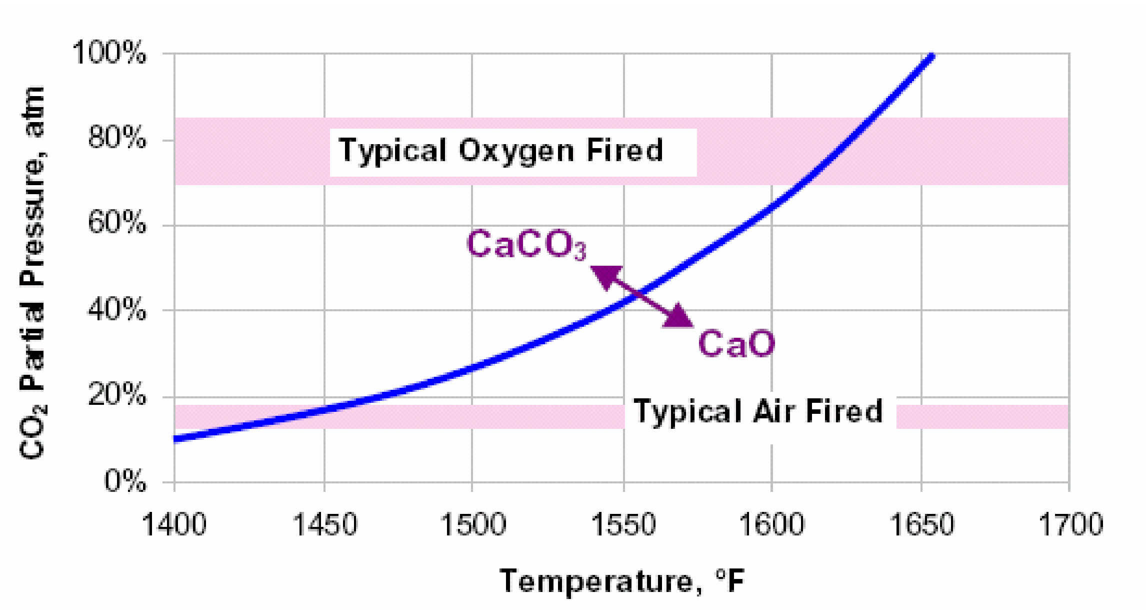
Sulfur Oxides

- **Sulfur removal with ash is increased by up to 30% (1.5 MW_t Air Liquide and B&W, 2003, IHI 2007), explained by higher kinetics of sulfation of ash due to high concentrations of SO_2 (Okazaki, 2003)**
- **An additional factor may be the direct sulfation of $CaCO_3$ which is not constrained by the problems of pore-mouth plugging encountered with CaO**

$$CaCO_3 + SO_2 + \frac{1}{2} O_2 = CaSO_4 + CO_2$$

•Recarbonation is observed by Alstom (2006) in CFB as flue gases cool

•For CFB operation at higher pressures will lead to direct sulfation in bed



"What is the purity of CO_2 for Transport" ENCAP, Dakota Gasification)

In the absence of regulation, one measure of the purity of the CO_2 for transport is the product of tne Dakota Gasification Plant now being piped to the Weyburn for enhanced oil recovery. A typical compositionof the gas product is: 96% CO_2, 2% C_2 + Hydrocarbons, 0.3 CH_4, 1% H_2S, 0.6 N_2, 0.01% O_2,

CO_2

- **CO_2 > 95%**
- **H_2O < 100 ppm**
- **H_2S < 1450 ppm**
- **Non-condensables (N_2, Ar, O_2) < 4%**
- **HC < 5%**
- **O_2 < 100 ppm**

The limit on non-condensables is driven by the cost of separating them from CO_2 during compression and imposes severe constraints on furnace inleakage for retrofits.

Concentration limits for on-site sequestration are uncertain, both technical and regulatory.

Also uncertain is the SO_2 concentration that can be tolerated in the recycle loop, and whether desulfurization before recycle is necessary for high sulfur coals

“What is the purity of CO_2 for Transport” ENCAP, Dakota Gasification)

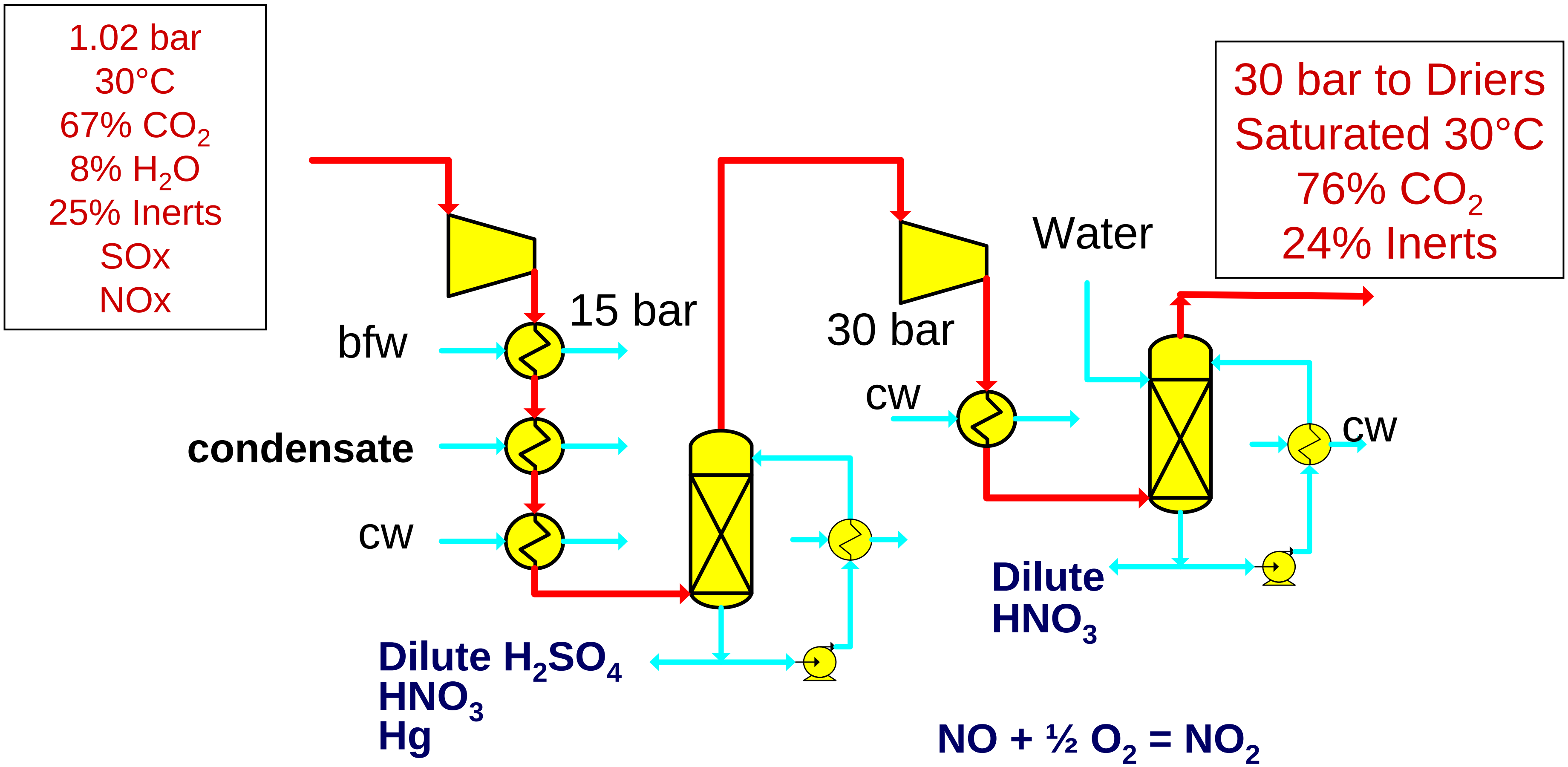
ENCAP guidelines and average concentrations from South Dakota Gasification plant (5 million tons successfully piped 200 miles to Weyburn field for EOR) are provided as guidelines of what to expect in the absence of current regulations.

The limit on non-condensables is driven by the cost of separating them from CO_2 during compression and imposes severe constraints on furnace inleakage for retrofits.

Component	ENCAP WP 1.1 EOR Guidelines molar	ENCAP WP 1.1 Severe Limit Case molar	Dakota Gasification Typical Concentration, molar
CO_2	> 90 %	> 95%	96 %
C_2 + Hydrocarbons	---	---	2 %
H_2S	<50 ppm	< 5 ppm	1 %
N_2	See Sum of Inerts	See Sum of Inerts	0.6 %
CH_4	---	---	0.3 %
O_2	100 ppm	100 ppm	0.01 %
Mercaptan & other sulfides	See individual cpds.	See individual cpds.	0.03 %
H_2O	<500 ppm	< 5 ppm	2 ppm
Sum of Inerts (N_2, O_2, Ar, CO)	< 4 %	< 4%	See O_2, N_2
SO_2	< 50 ppm	< 5 ppm	---
HCN	---	5 ppm	---
Mercaptans	< 50 ppm	10 ppm	---
NO	---	< 5 ppm	---
COS	< 50 ppm	10 ppm	---

CO_2 Compression and Purification System – Removal of SO_2, NOx and Hg (Air Products, 2006)

- **SO_2 removal: 100% NOx removal: 90-99%**

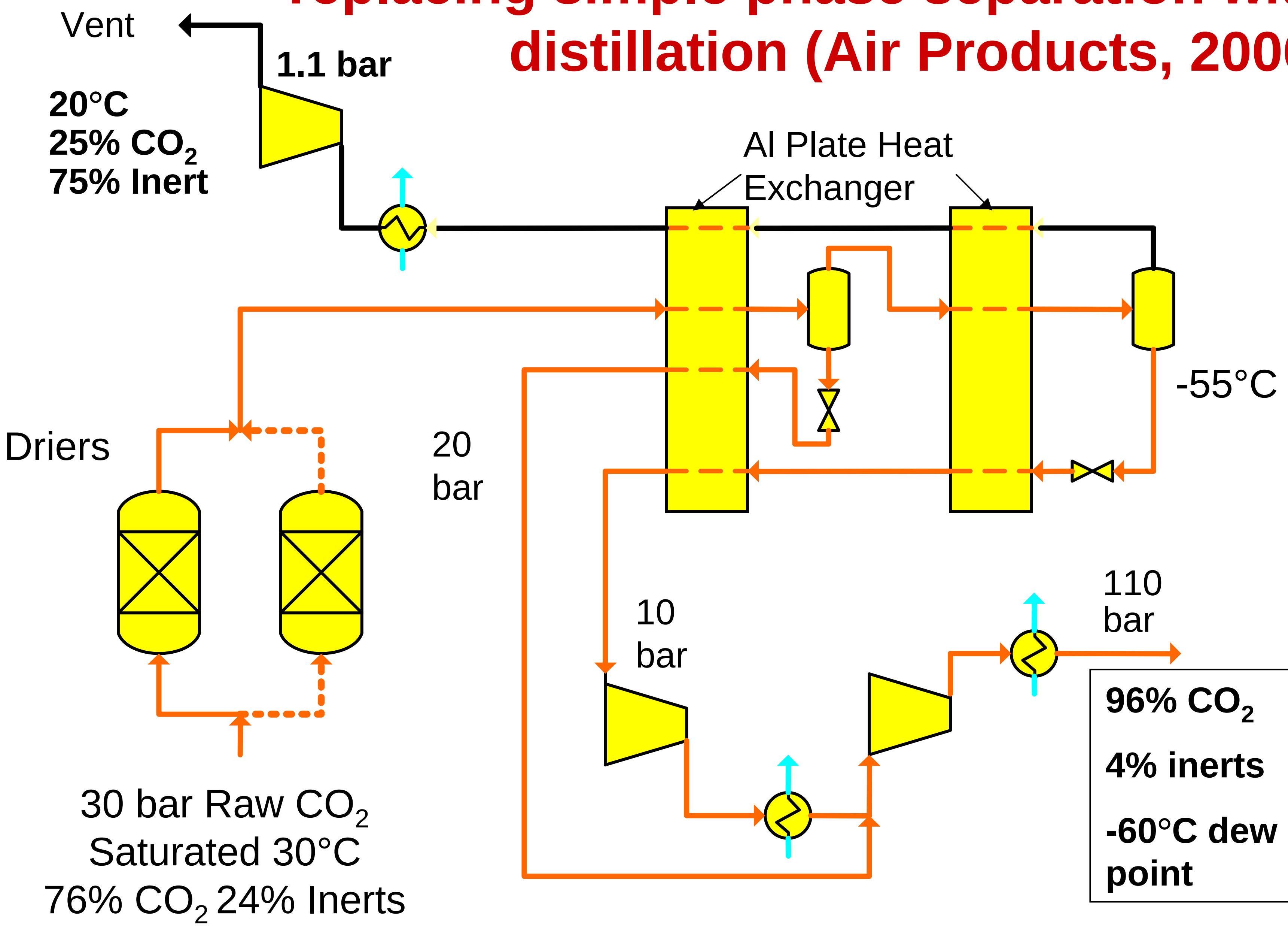


$NO + ½ O_2 = NO_2$
$NO_2 + SO_2 = SO_3 + NO$
$SO_3 + H_2O = H_2SO_4$
$H_2O + NO_2 = HNO_3 + HNO_2$

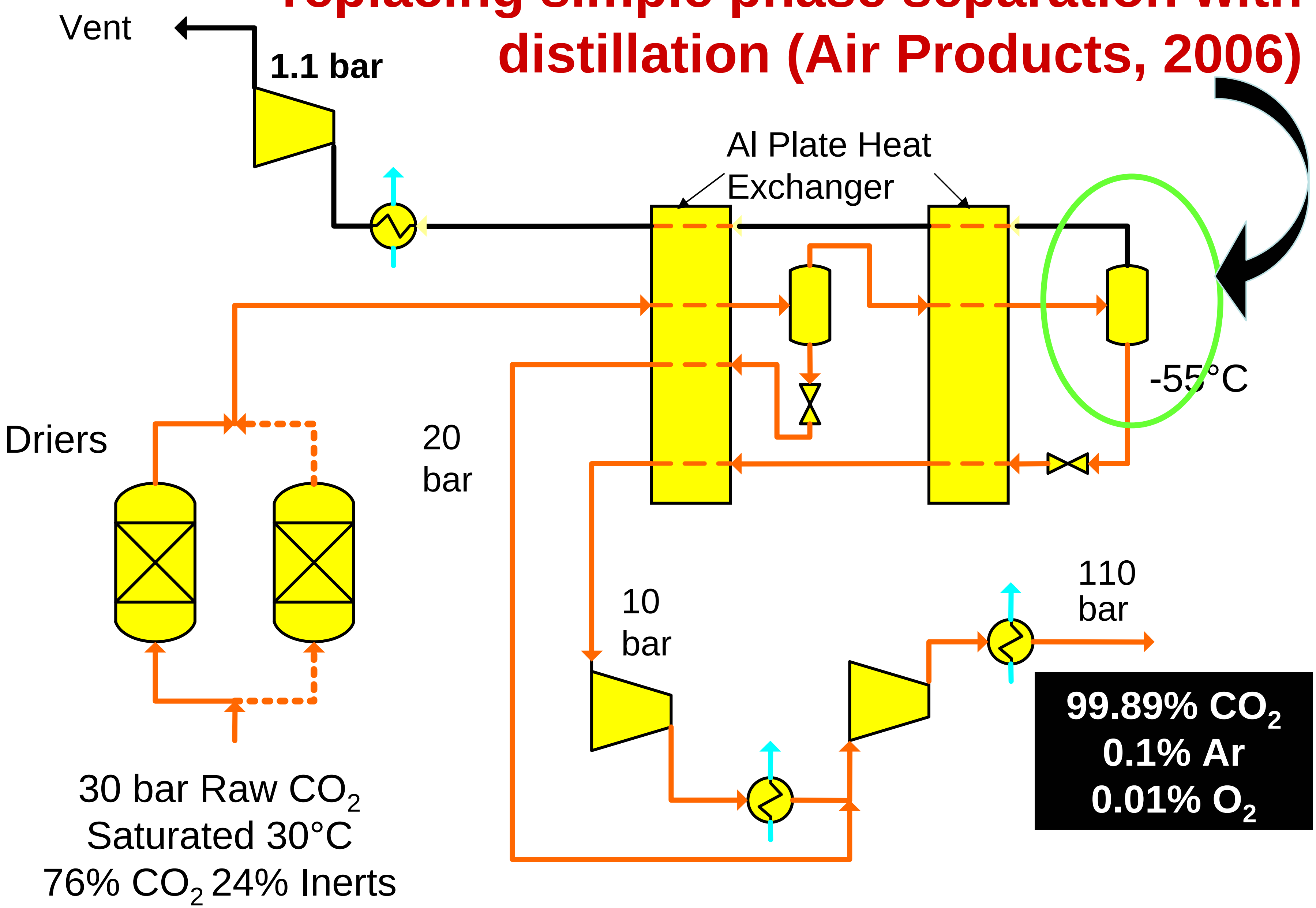
SOx/NOx Removal – Key Features (Air Products, 2006)

- Adiabatic compression to 15 bar:
  - No interstage water removal
  - All Water and SOx removed at one place
- NO acts as a catalyst
  - NO is oxidised to NO_2 and then NO_2 oxidises SO_2 to SO_3: The Lead Chamber Process
- Hg will also be removed, reacting with the nitric acid that is formed

Oxygen can be reduced to low level by replacing simple phase separation with distillation (Air Products, 2006)



Oxygen can be reduced to low level by replacing simple phase separation with distillation (Air Products, 2006)



Sources of Non-condensables (Kather for details)

- Air leakage
  - Mainly in air heaters (especially Lungstrom design) and ESPs; values typically > 3% increasing with age of plant
- With oxygen from ASU
  - Cost of oxygen can be reduced with reduction in purity. Optimum purity of 95% O_2, 3% Ar, 2% N suggested, corresponding to an increment of about 2.3 % Ar, 1.6% N_2 in flue gases
- From excess oxidant
  - 3% Oxygen in product gas (~4% excess for O_2 firing versus 18% for air)

Combustion considerations

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

"What are the data available in characterization and performance of different types of coal under the firing conditions of an $O_2/CO_2/H_2O$ environment?"

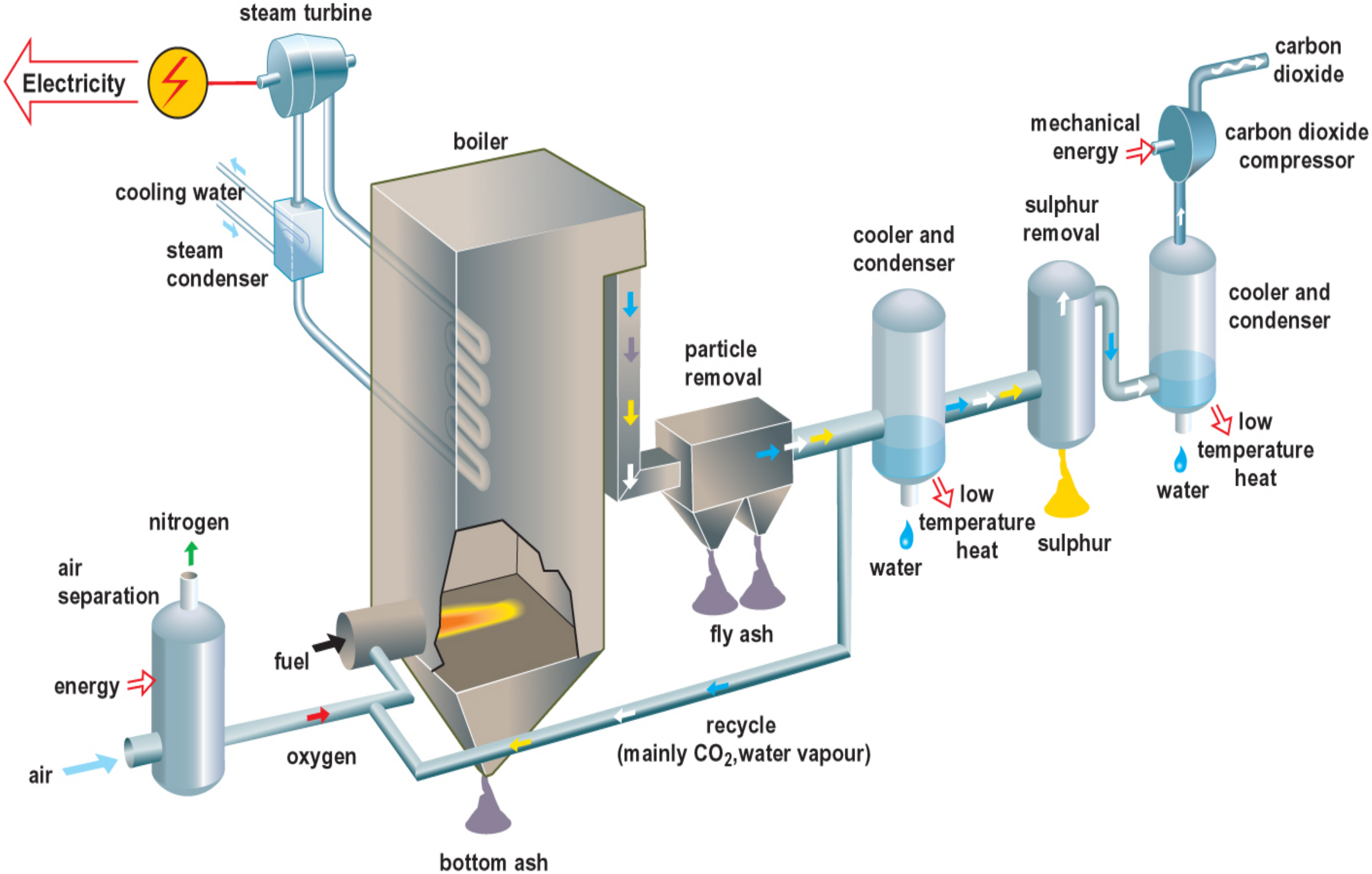
Combustion ramifications of replacing N_2 by CO_2

- **Flame stability (Wall, Wendt & Eddings, Hals, Zanganeh)**
  - "Flame stability performance was unchanged in spite of use of oxygen deficient recycle flue gas as the transport medium for the pulverized coal" (Payne et al, 1989). Issues of scale up, design, turn down, design tools…need to be addressed.
  - Oxygen in near burner region can greatly increase flame stability and be used to advantage for high velocity burners
  - Use of oxygen deficient recycle flue gas has not impacted flame stability
  - CO_2 is known to decrease flammability limits and soot formation
- **Carbon Burnout (Shaddix, Maier)**
  - Increased residence time and augmentation of the char gasification rate by reaction with carbon dioxide and water vapor will enhance char burnout, supported by data on reduction in carbon in ash on conversion to oxy-combustion (Payne et al., 1989, IHI, 2007).

Outline

- Oxy-fuel combustion principles
  - Heat Transfer
  - Stoichiometric considerations
  - Emissions
  - Combustion Consideration
- External Recycle for Greenfield or Retrofit Applications
- Internal Recycle for New Plants (Reducing Plant Cost)
- Reducing the Cost of Oxygen
- Concluding comments

External Recycle (Strömberg, 2004)



Status of 'Practical Plant Operation and Safety Issues'

Panel CES, Total, SakPower, Vattenfall, Jupiter

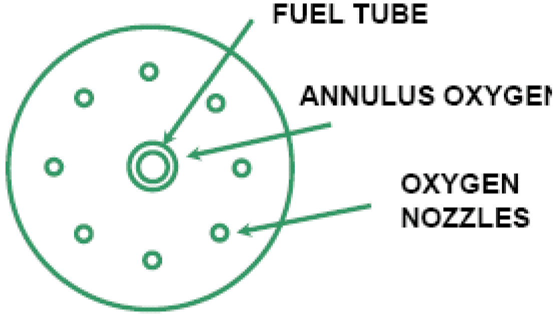
- **Existing Pilot Scale (< 5 MW_t)**
  - **EER (CA), 3.2 MW; IFRF (Netherlands), 2.5 MW; IHI (Japan); Air Liquide, B&W (OH), 1.5 MW; CANMET (Canada), 0.3 MW; Alstom (CT), 3.0 MW CFB, IVD (Germany) 0.5 MW**
- **Planned Pilot Demonstration (>20 MW_t)**
  - **Vattenfall 30 MW_t Schwarze Pumpe Germany. Ground breaking 5/06**

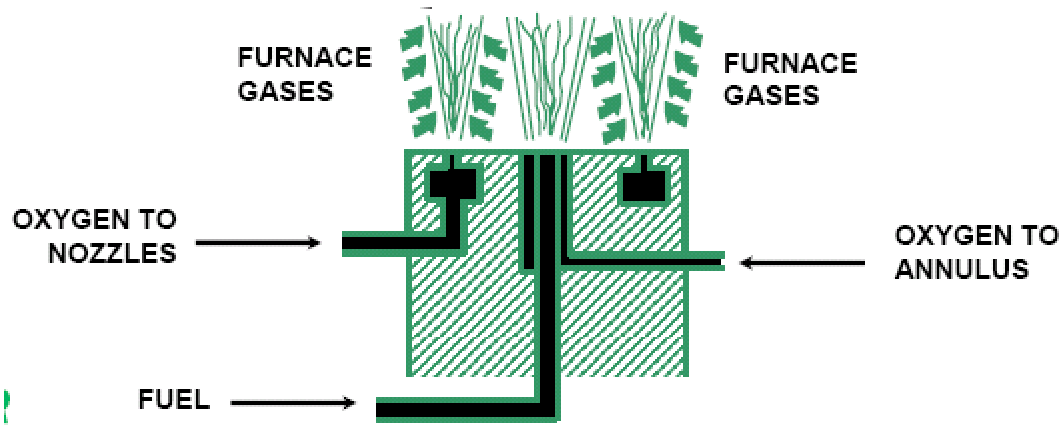
    Japan (IHI) –Australia (Queensland) Oxy-Fired Retrofit with oxygen plant, CO_2 compression and sequestration (including combustion and heat transfer evaluation); PF boiler (Callide A 30 MWe Unit owned by CS Energy).
  - **Hamilton (OH) B&W 24 MW_e retrofit**
- **Commercial Installations**
  - **Commitment to oxy-fuel evident from investments of € 50 M ($63.6 M) for Vattenfall pilot and A$ 180 M ($138 M) for Callide retrofit, SaskPower: potential $ 1.5 billion 300 MWe**
  - **Applications for EOR**
- **Economic Assessments**
  - **Many with general conclusion that IGCC, Oxyfuel, and Amine scrubbing, with cost of IGCC ≅ Oxyfuel (depending upon coals used, assumptions made) > Amine scrubbing.**

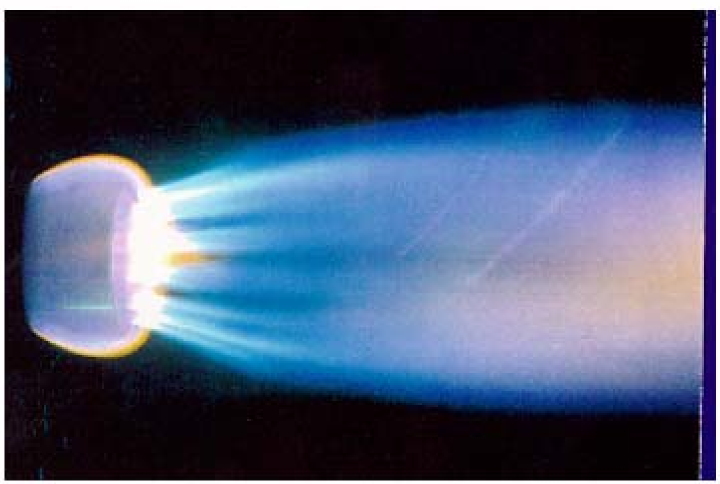
Outline

- Oxy-fuel combustion principles
  - Heat Transfer
  - Stoichiometric considerations
  - Emissions
  - Combustion Consideration
- External Recycle for Greenfield or Retrofit Applications
- Internal Recycle for New Plants (Reducing Plant Cost)
- Reducing the Cost of Oxygen
- Concluding comments

Aspirating (A) burner for having oxygen designed to mimic air at fuel jet (Kobayashi, 2005)



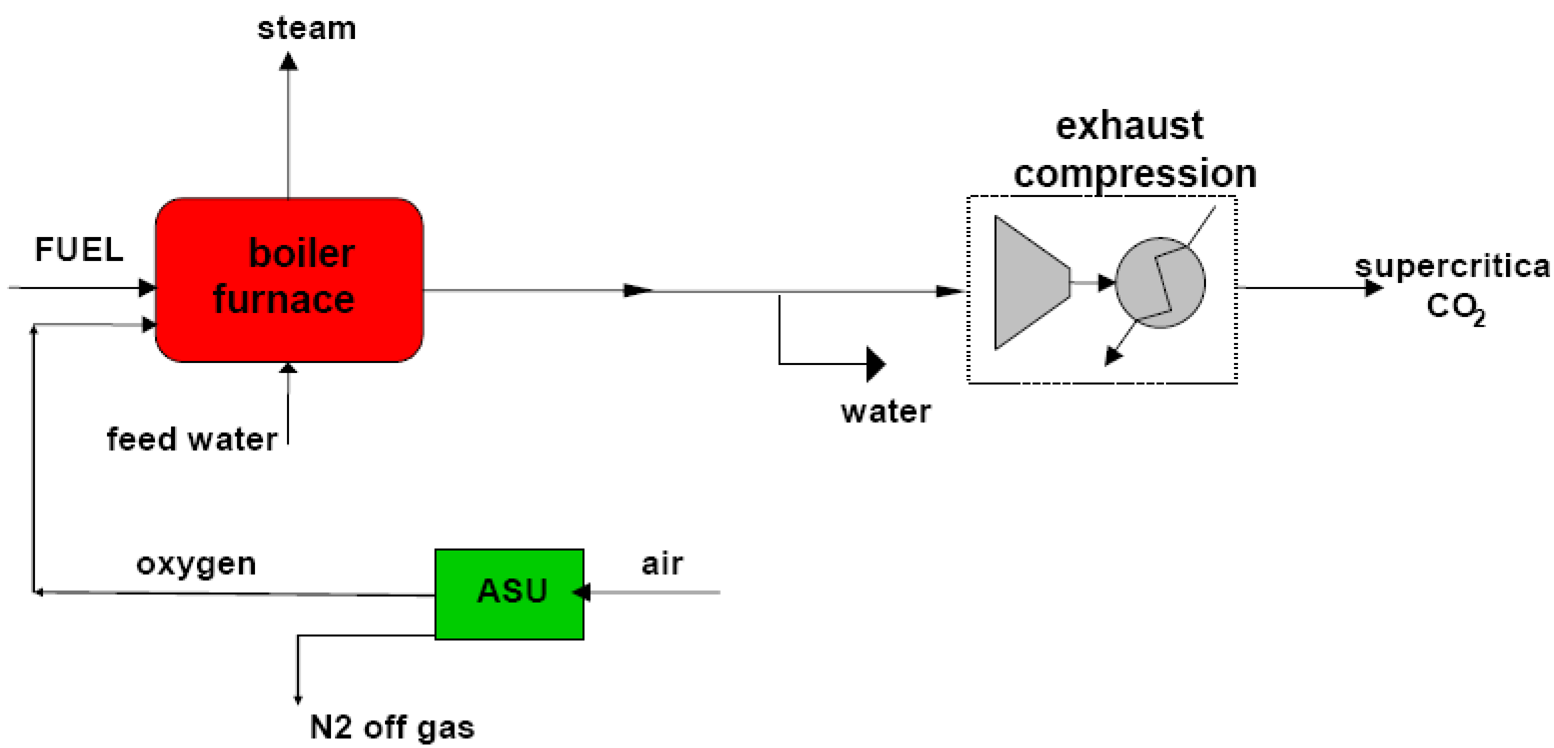




Picture here is for a J Burner one of the family of aspirating burners

Aspirating burners using internal gas recirculation are widely used in industry (e.g., steel reheating, and soaking pits)

New Plant Design with Internal Flue Gas Recycle (Praxair, ’05)

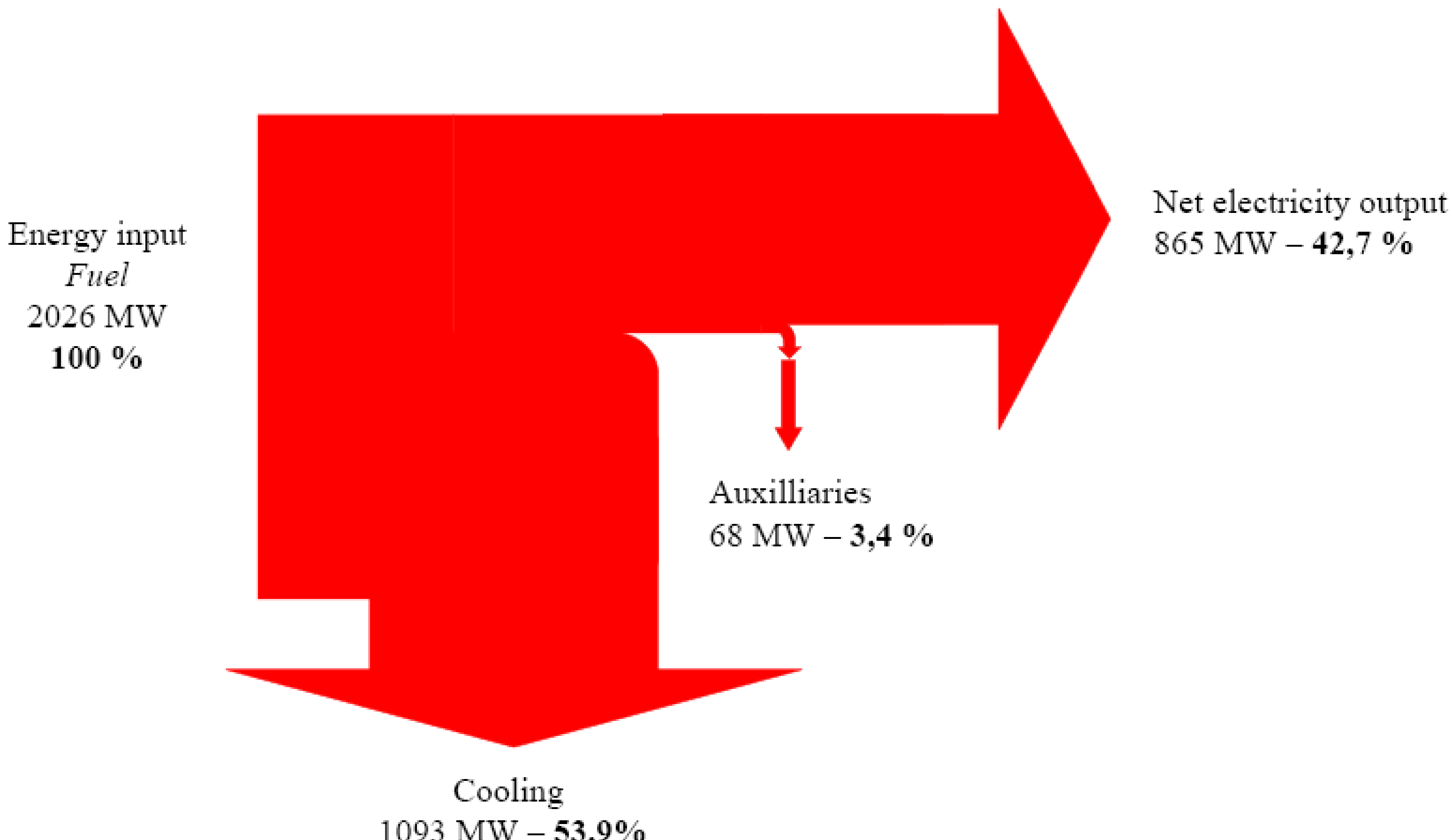


New boiler designs are needed where most of heat transfer surface is in radiant section since 70 - 80% of available energy for oxyfiring is above typical exit temperatures (2000 – 2300 F, 1400 – 1550 K). Flue gas volume will be 24% that of air fired system.

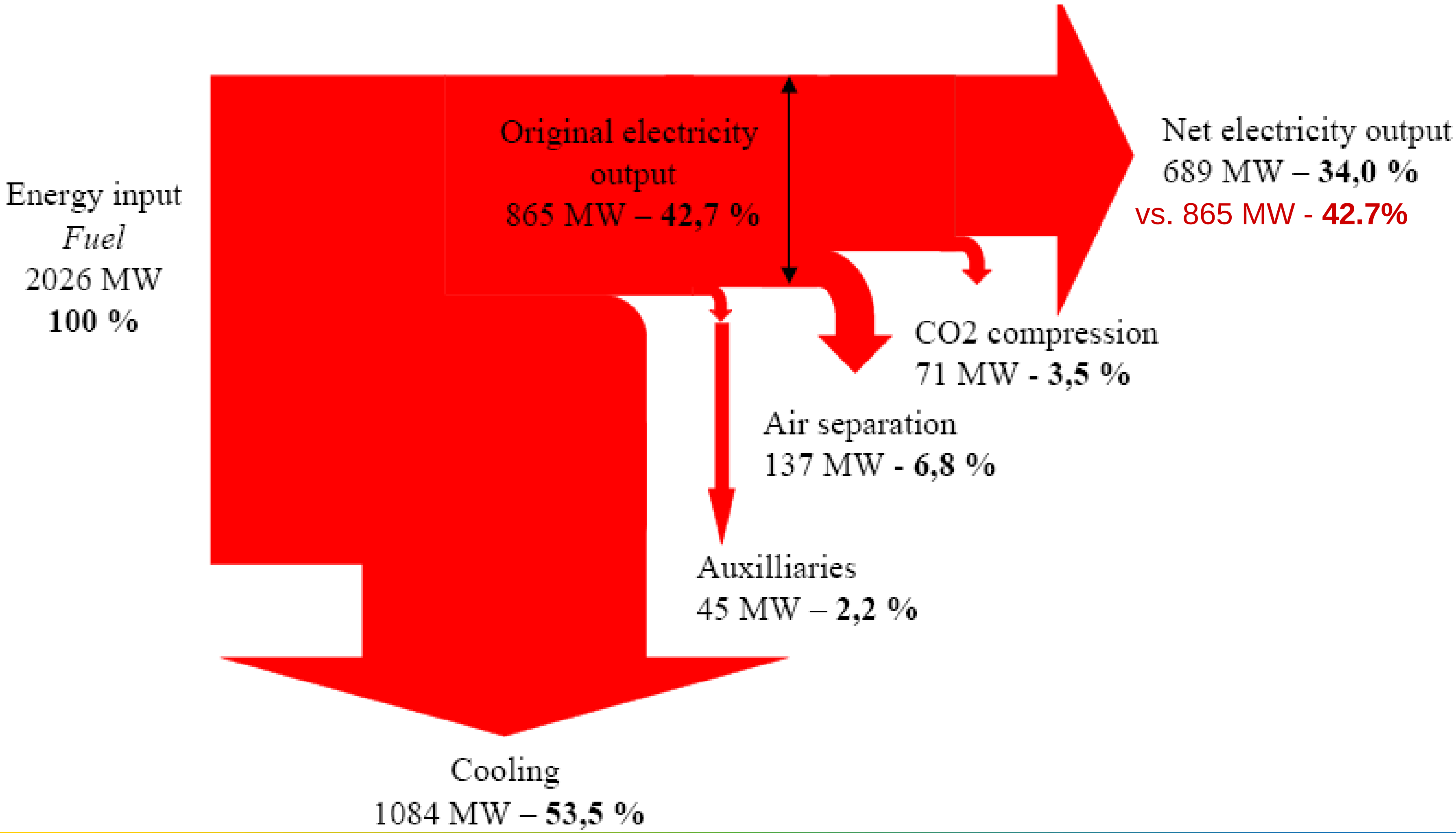
Outline

- Oxy-fuel combustion principles
  - Heat Transfer
  - Stoichiometric considerations
  - Emissions
  - Combustion Consideration
- External Recycle for Greenfield or Retrofit Applications (Reducing Plant Cost)
- Internal Recycle for New Plants
- Reducing the Cost of Oxygen
- Concluding comments

Energy flows for Conventional Lignite-Fired Boiler (Stromberg, 2004)



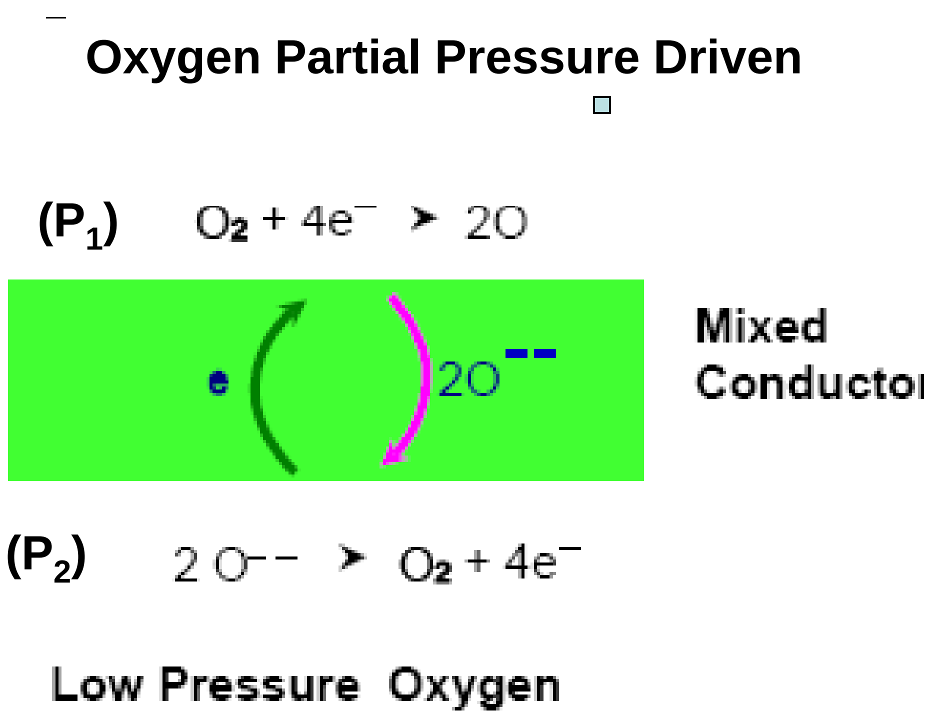
Energy Flows for the case of Oxy-Fuel Firing Showing Losses with Air Separation Unit and CO_2 Compression (Stromberg, '04)



Cost of Producing Oxygen (Praxair, 2005)

- Current technologies to produce 95% purity oxygen require ~ 200 kwh/ton O_2
- Theoretical energy required to compress oxygen from 0.21 to 1 atmosphere is about 30 kwh/ton O_2
- There is potential for enormous savings with innovative designs
  - Chemical looping combustion being pursued by several groups [Chalmers (Sweden), GE-EER (USA), Zaragosa (Spain), KIER (Korea), NNTU (Norway),…] using Fe, Mn, Cu, Ni based oxygen carriers.
  - CO_2 in-furnace capture and recovery using solid sorbents (e.g., CO_2 wheel and lithium sulfate or hydrotalcite)
  - New concept by Praxair using oxygen transport membranes appears to be exciting alternative.

Oxygen Transport Membranes Integrated into Boiler Offer Potential for Major Cost Reduction (Praxair, 2005)

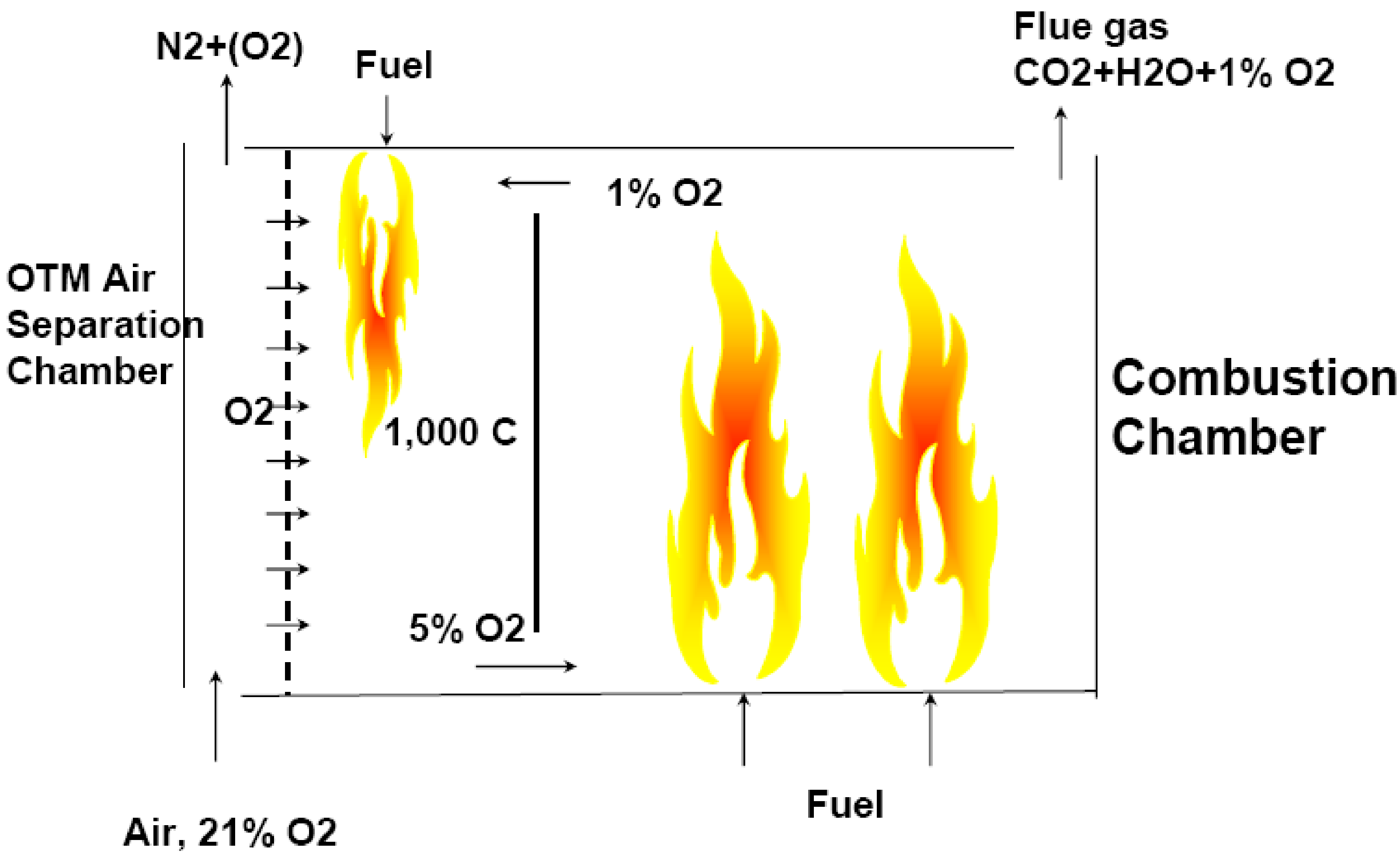


P is oxygen partial pressure

O_2 Flux = C·ln(P_1/P_2)

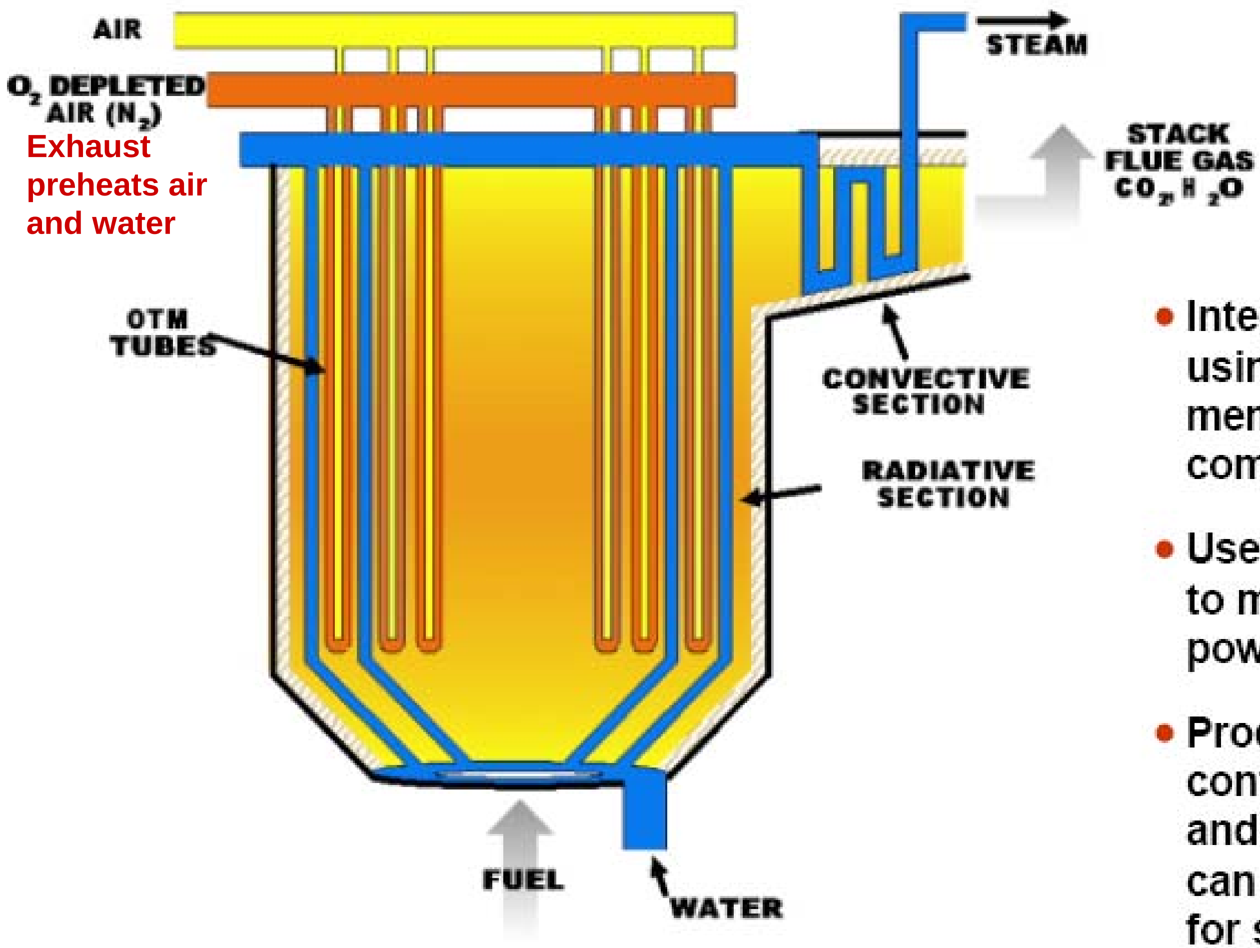
High fluxes can be obtained with $P_1/P_2 > 3$ achievable by compressing air to 14.3 atmospheres (P_1 = 14.3 x 0.21 = 3, P_2 =1) to produce pure O_2 corresponding to an ideal compression power of 80 kwh/ton O_2, basis for current ITM processes, e.g., DOE/Air Product (target 30% cost reduction) OR by using air at 1 atm (P_1=0.21) and dilute oxygen combustion at < 7% O_2 (P_2< 0.07)

Conceptual sketch of OTM-Dilute oxygen combustion (Praxair, 2005)



One Praxair Concept for OTM Furnace

Because of the nitrogen elimination greater fraction of energy is transferred in radiative section (Praxair, '05)



- 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.

•OTM boiler reduces air separation power by 90%

Outline

- Oxy-fuel combustion principles
  - Heat Transfer
  - Stoichiometric considerations
  - Emissions
  - Combustion Consideration
- External Recycle for Greenfield and Retrofit Applications
- Internal Recycle for New Plants
- Reducing the Cost of Oxygen
- Concluding comments

Concluding Comments

- **Laboratory and pilot scale studies have demonstrated the feasibility of near term commercial implementation of oxy-combustion for CO_2 production. Advantages to industry over IGCC are reliability, availability, and familiarity. If emissions of carbon are to be stabilized it is important to have implementation and wide-scale deployment of CCS in the near future. However, there is a need to develop the 'clean coal' image for oxy-combustion that IGCC has succeeded in achieving.**

- **Long term prospects, especially the involvement of developing economies, depend on reducing costs of oxy-fuel or other emerging CCS technologies**
  - **Near term reduction in cost: CFBC first, Internal Gas Recycle later for capital costs, ITM for operating costs.**
  - **Longer term potential for major cost reductions should come from chemical looping and in-furnace OTM.**

ALSTOM

Advanced Combustion Technology: OXYFIRING TO ENABLE CO_2 CAPTURE

Advanced Combustion Technology:

OXYFIRING TO ENABLE CO_2 CAPTURE

W.A. Fiveland and Nsakala Nsakala

ALSTOM Power Inc.

Frank Kluger

ALSTOM Power Boiler GmbH

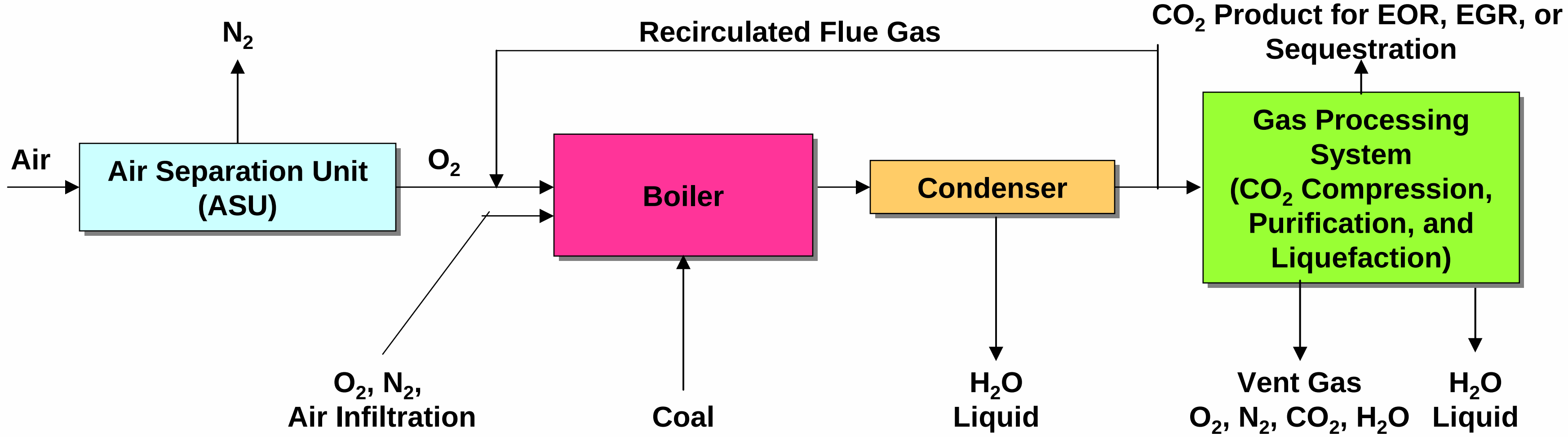
Fredrik Brogaard

Alstom Power Sweden AB

Oxygen firing: Concept

Fuel is burned in a boiler in a mixture of oxygen and recirculated flue gas (principally CO_2), essentially eliminating the presence of atmospheric nitrogen in the flue gas. The resulting flue gas is comprised of primarily CO_2 and H_2O vapor along with some N_2, O_2, and trace gases like SO_2, and NO_X. Consequently:

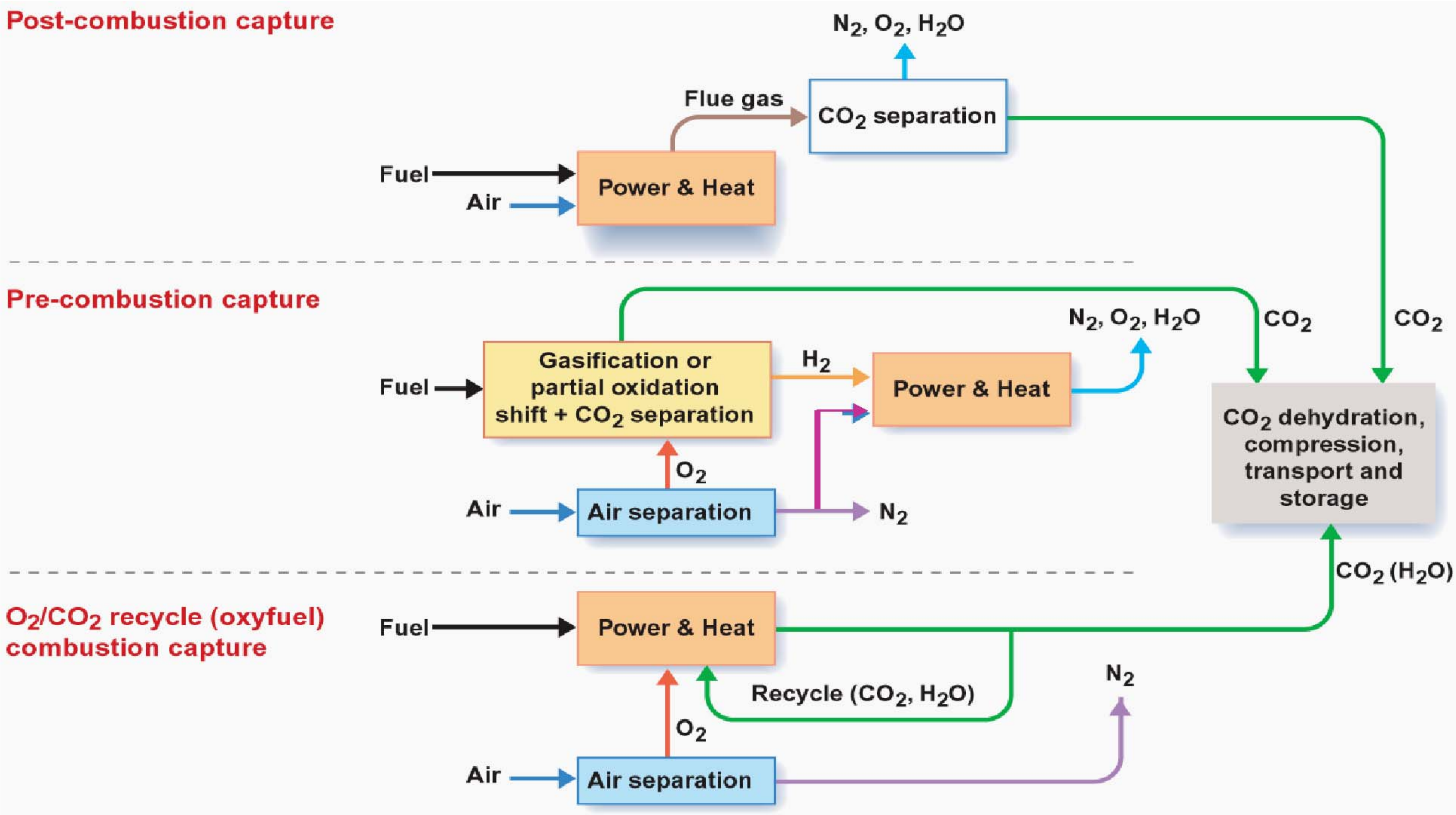
- **The flue gas can be processed relatively easily (through rectification or distillation) to enrich the CO_2 content in the product gas to $96\text{-}99^+$ percent for use in enhanced oil or gas recovery (EOR or EGR), or**
- **The flue gas is simply dried and compressed for sequestration only**



Today’s Discussion

- **Overview**
  - Conventional oxy-firing
  - Advanced concepts
  - Economics of recent studies
  - Ongoing test programs

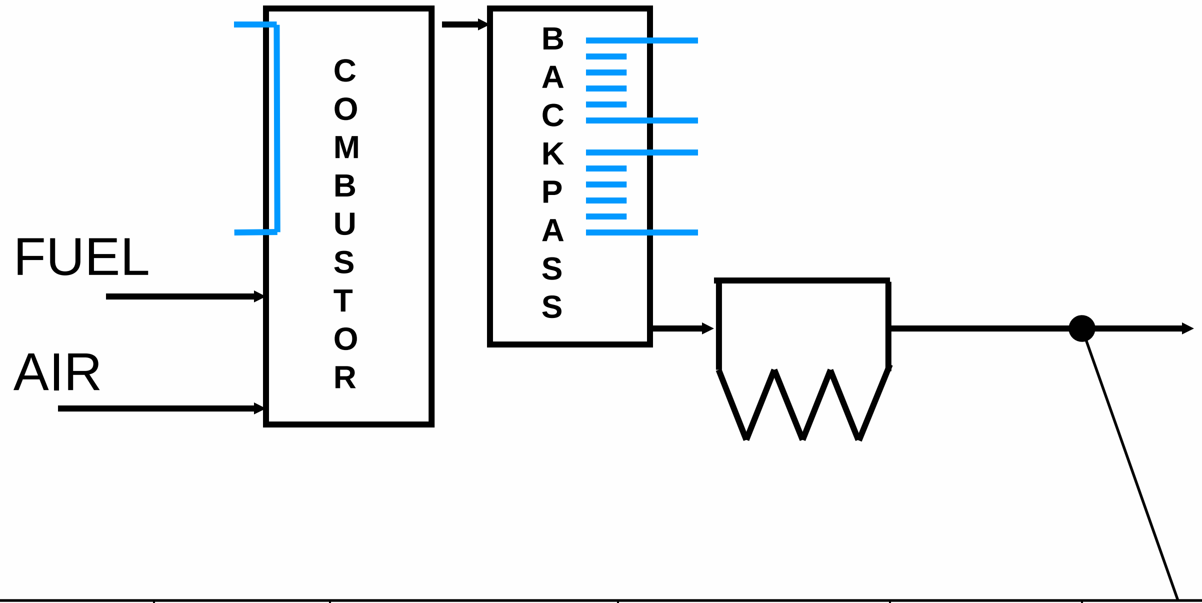
CO_2 Capture Options



CO_2 Capture Options

	Oxidant	CO_2 Removal
Post-combustion	Air Fired	Extract from Flue Gas
Pre-combustion	O_2 for Gasification Air for Final Combustion	Shift CO to CO_2 Extract from Fuel Gas
Oxyfiring	O_2 for Combustion	Dry and Purify Flue Gas

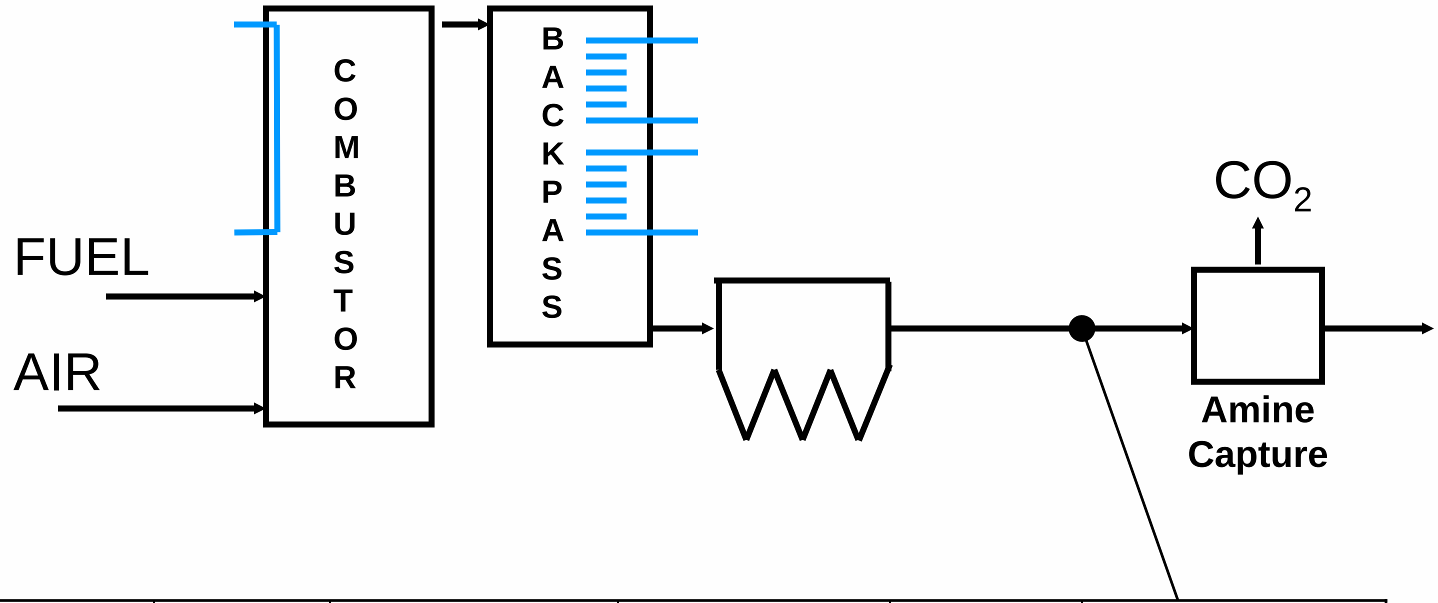
Conventional Firing



	N_2	CO_2	H_2O	O_2	Rel Vol
AIR	75	15	7	3	100

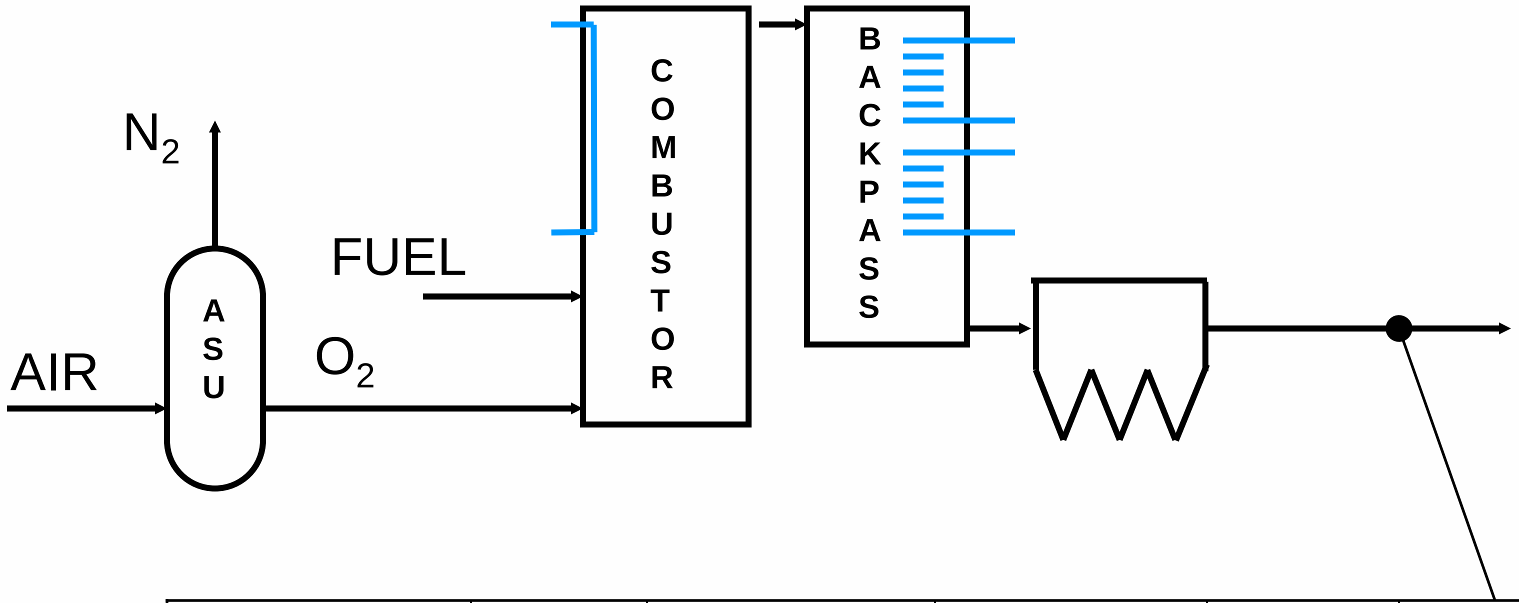
ALSTOM

Conventional Firing with Amine Scrubbing



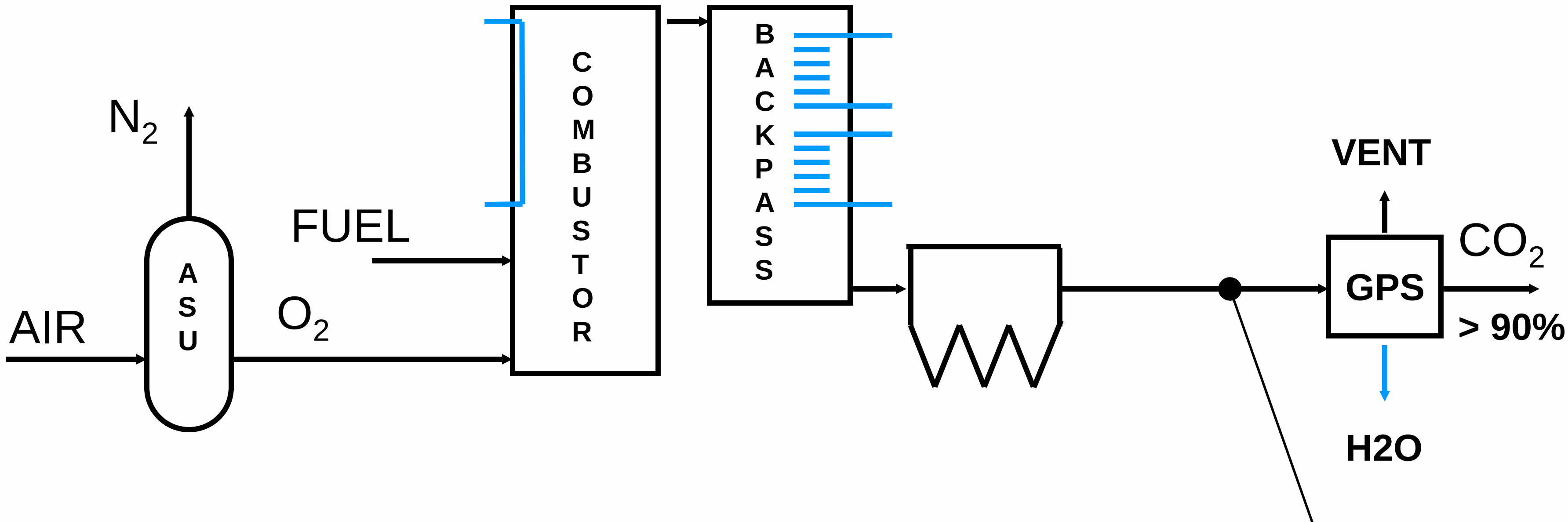
	N_2	CO_2	H_2O	O_2	Rel Vol
AIR	75	15	7	3	100

Conventional Firing using ASU to Produce a Stream of Oxygen



	N_2	CO_2	H_2O	O_2	Rel Vol
AIR	75	15	7	3	100
100% O_2	5	67	25	3	22

Conventional Firing with ASU and Drying to Purify the CO_2 stream

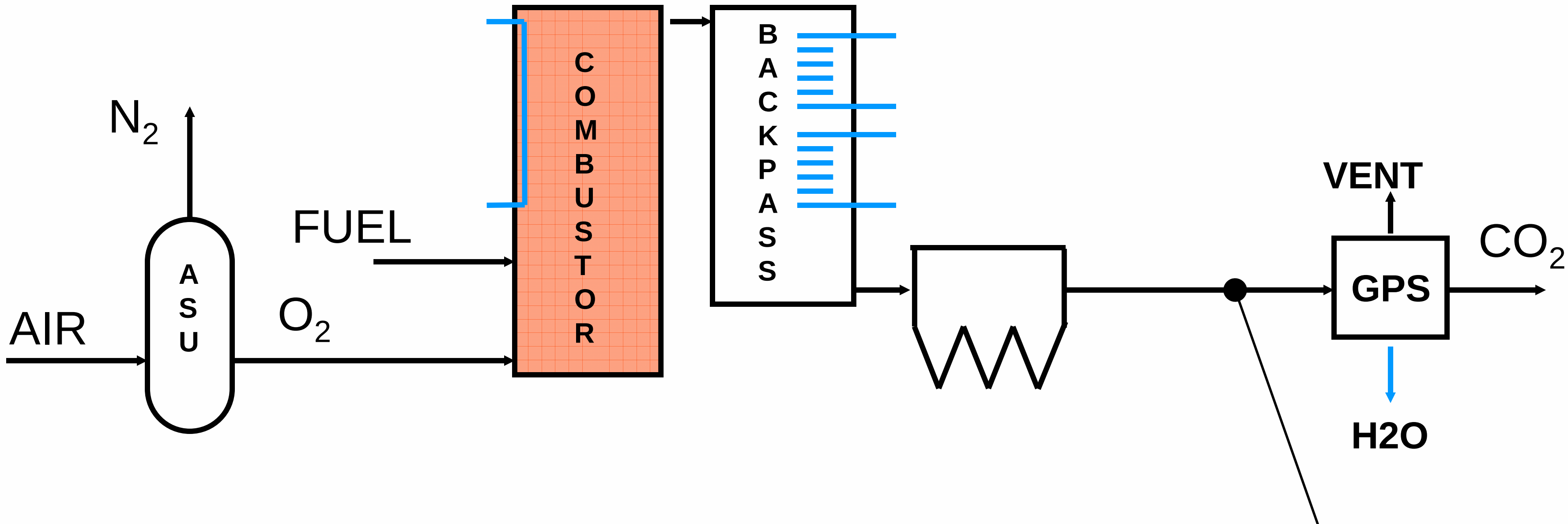


	N_2	CO_2	H_2O	O_2	Rel Vol
AIR	75	15	7	3	100
O_2	5	67	25	3	22

ALSTOM

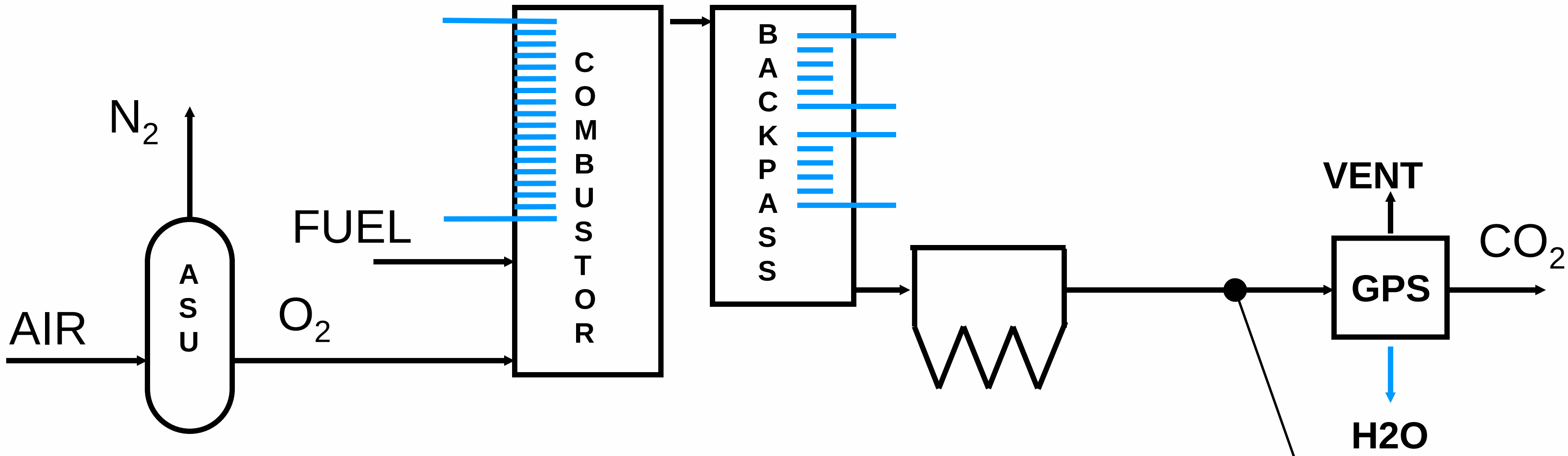
Three Oxygen-fired firing options

Conventional Firing with ASU produces high combustor temperatures



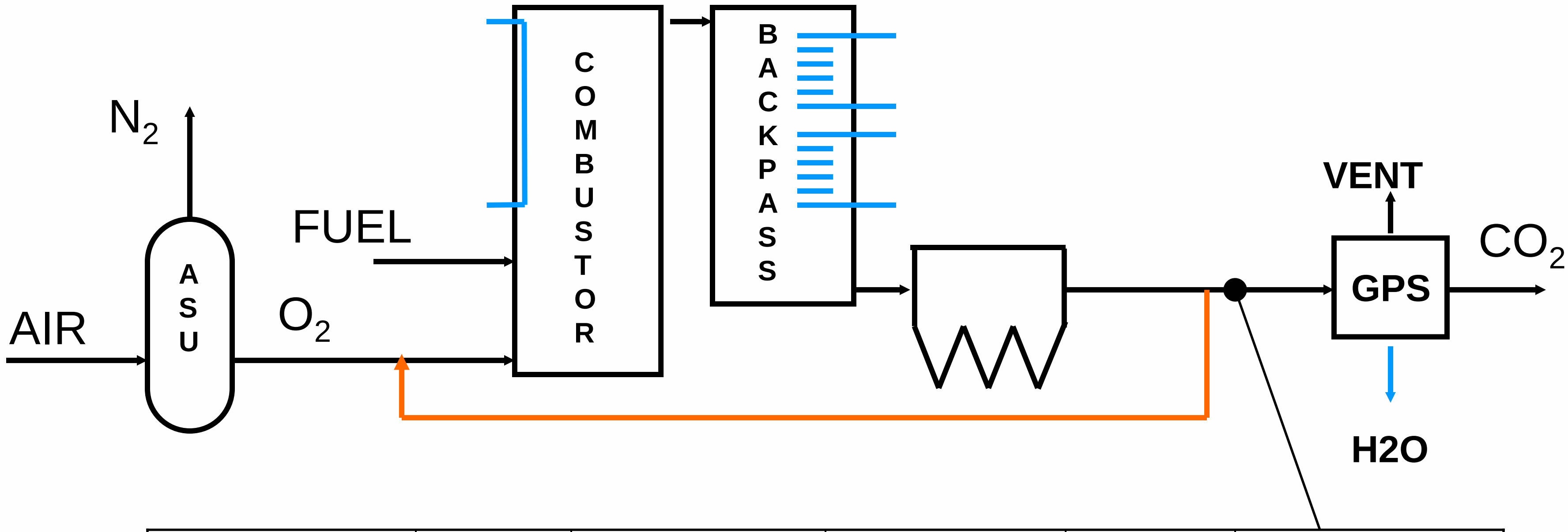
	N_2	CO_2	H_2O	O_2	Rel Vol
AIR	75	15	7	3	100
O_2	5	67	25	3	22

Combustor temperatures can be mitigated with upper furnace heat absorption



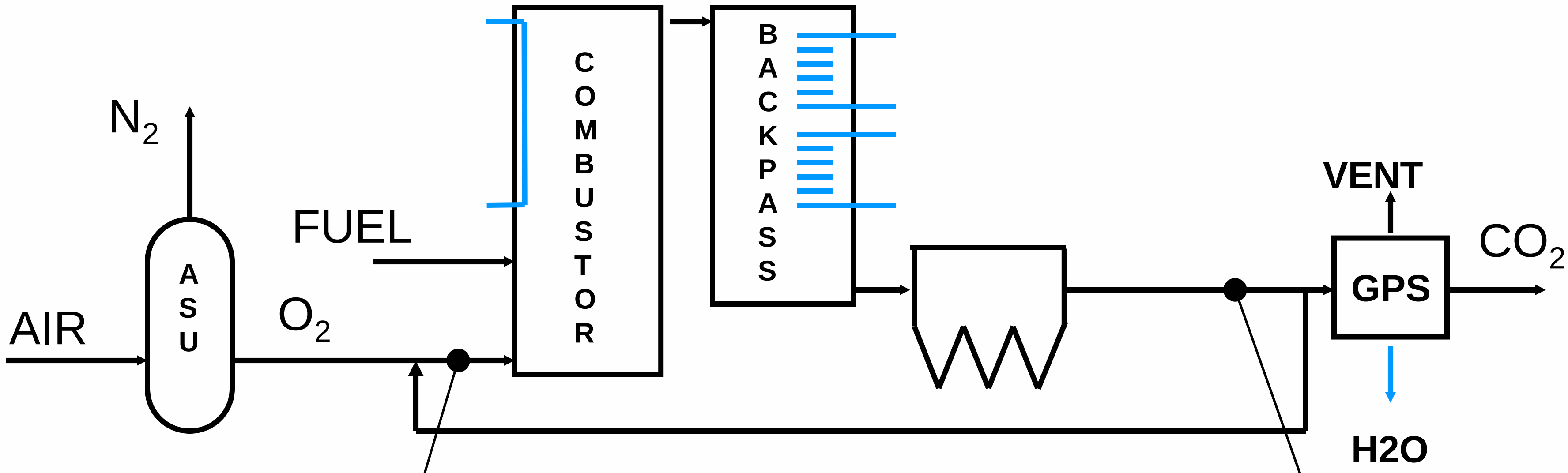
	N_2	CO_2	H_2O	O_2	Rel Vol
AIR	75	15	7	3	100
O_2	5	67	25	3	22

Combustor temperatures can be mitigated with flue gas recirculation



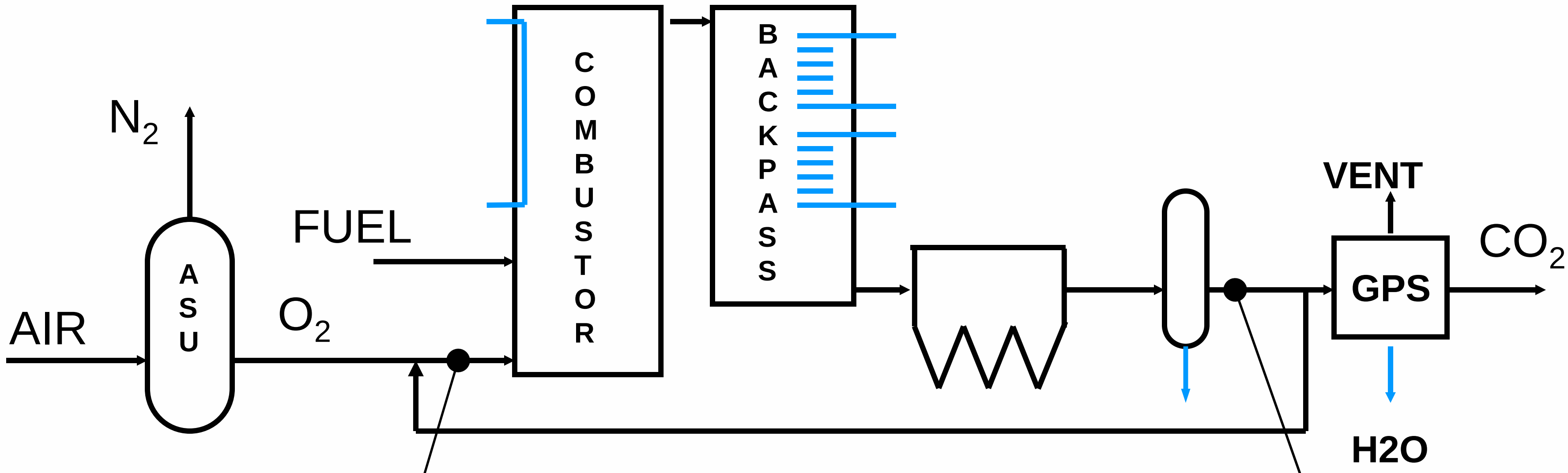
	N_2	CO_2	H_2O	O_2	Rel Vol
AIR	75	15	7	3	100
O_2	5	67	25	3	22

Retrofit option: Recirculate flue gas to a 30% O_2 blend maintains unit performance



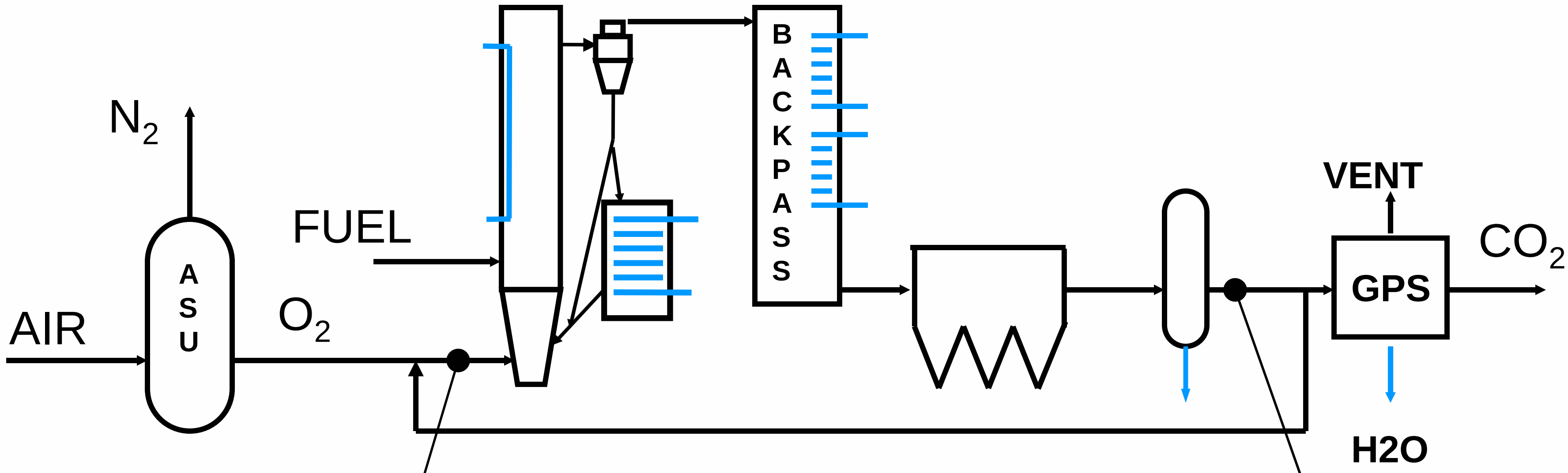
	N_2	CO_2	H_2O	O_2	Rel Vol
AIR	75	15	7	3	100
O_2	5	67	25	3	22
30% O_2	5	67	25	3	64

Retrofit option: Recirculate flue gas to a 30% O_2 blend maintains unit performance



	N_2	CO_2	H_2O	O_2	Rel Vol
AIR	75	15	7	3	100
O_2	5	67	25	3	22
30% O_2	6	83.5	7	3.5	65

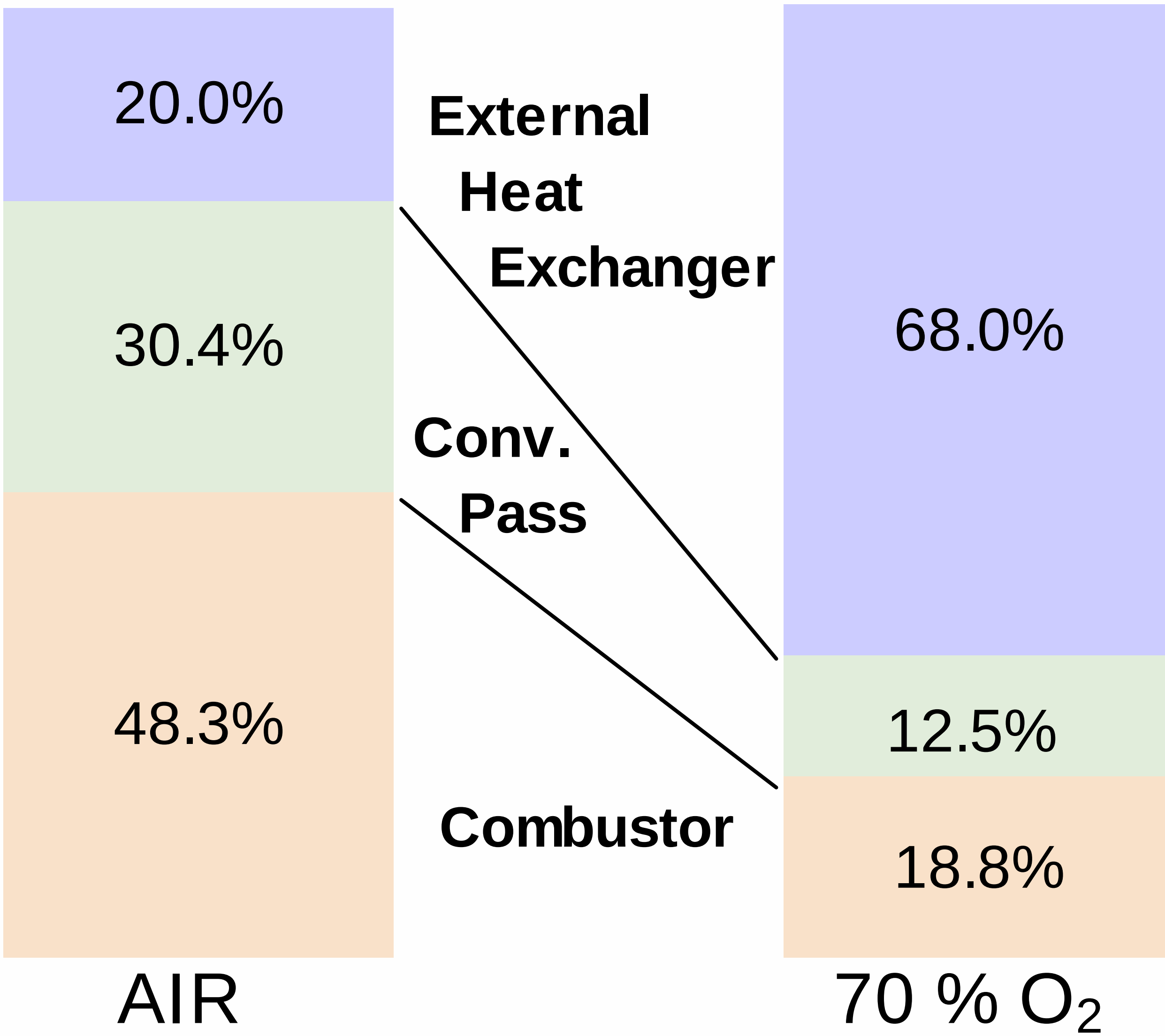
Greenfield option: Circulating Fluidized Bed reduces recirculation of flue gas



	N_2	CO_2	H_2O	O_2	Rel Vol
AIR	75	15	7	3	100
O_2	5	67	25	3	22
70% O_2	6	83.5	7	3.5	28

ALSTOM

CFB Heat Duties for Air and Oxy fired systems



Overview of ALSTOM Studies

Developments Related to Oxy-firing for CO_2 Capture

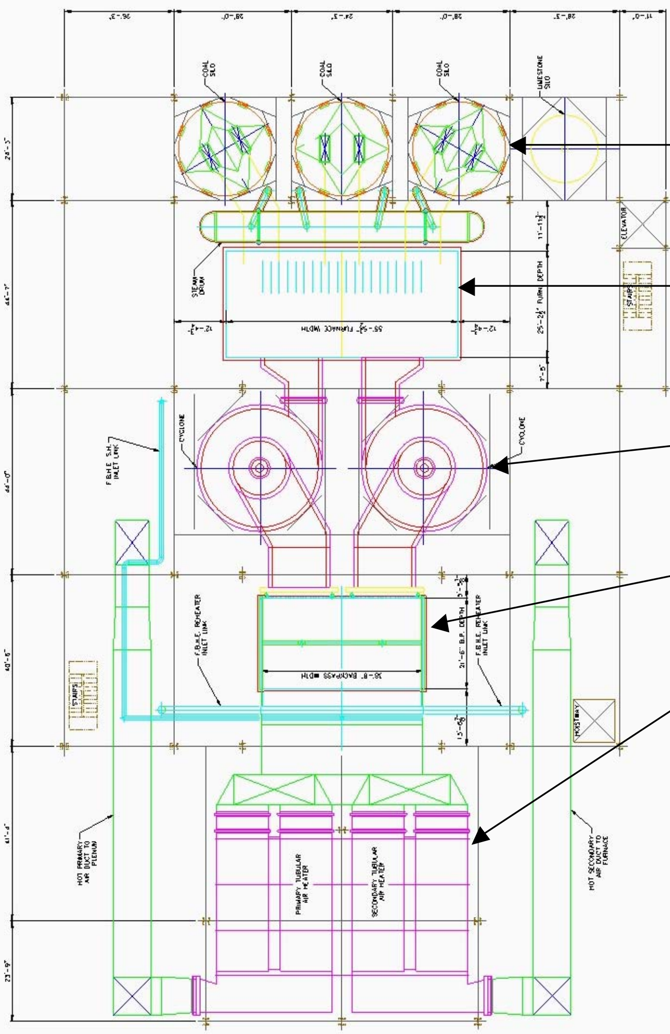
ALSTOM CO_2 Capture Efforts

1998	ALSTOM	Technical Feasibility of a CO_2/O_2 Combustion Retrofit to an Existing Coal-Fired Bolier for CO_2 Extraction
1999	TransAlta	Preliminary Design and Costing of a CO_2/O_2 Combustion Retrofit to an Existing Coal-Fired Bolier for CO_2 Extraction
1999	ABB	Investigation of Ceramic Oxygen Transport Membrane Processes with Coal Fired Power Plants
2000	Suncor	CFB Boiler Integrated with 300 Tonnes per Day CO_2 Removal System for Suncor Thermal Solvent Process Project
2000		ext Generation CO_2
2001		e Percentage for
1999 - 2001	OCDO / DOE / ALSTOM	Engineering Feasibilty and Economics of CO_2 Capture on an Existing Coal-Fired Power Plant
2001 - 2004	DOE / ALSTOM	Greenhouse Gas Emissions Control by Oxygen Firing in Circulating Fluidized Bed Boilers
2002 - 2003	EU	GRACE – Chemical Looping Combustion – Feasibility Study
2003 - 2004	ADEME / ALSTOM	CO_2 Capture – (cascade cryogenics) – ECS/BUB
2003 - 2004	ADEME / ALSTOM	CO_2 Capture - Calcium Cycle
2003 - 2005	DOE / ALSTOM	Hybrid Combustion Gasification Chemical Looping Coal Power
2003 - 2005	ADEME	EDF - 2015
2003 - 2006	EU	ENCAP
2004	EU / IPFP6	ENCAP (Oxyfiring – Chemical Looping)
2004 - 2006	DOE / ALSTOM	Commercialization Development of O_2-Fired CFB for Greenhouse Gas Control
2005 - 2006	DOE	CO_2 Capture from Existing Fleet Feasibility Study
2006 – 2009	DOE / BOC / ALSTOM	Pilot Scale Demonstration of CAR Technology on Oxygen Boilers

12 of 18 CO_2 studies focused on O_2 firing: a variety of partners EU, DOE, State agencies and utilities

Advanced O_2 Technologies

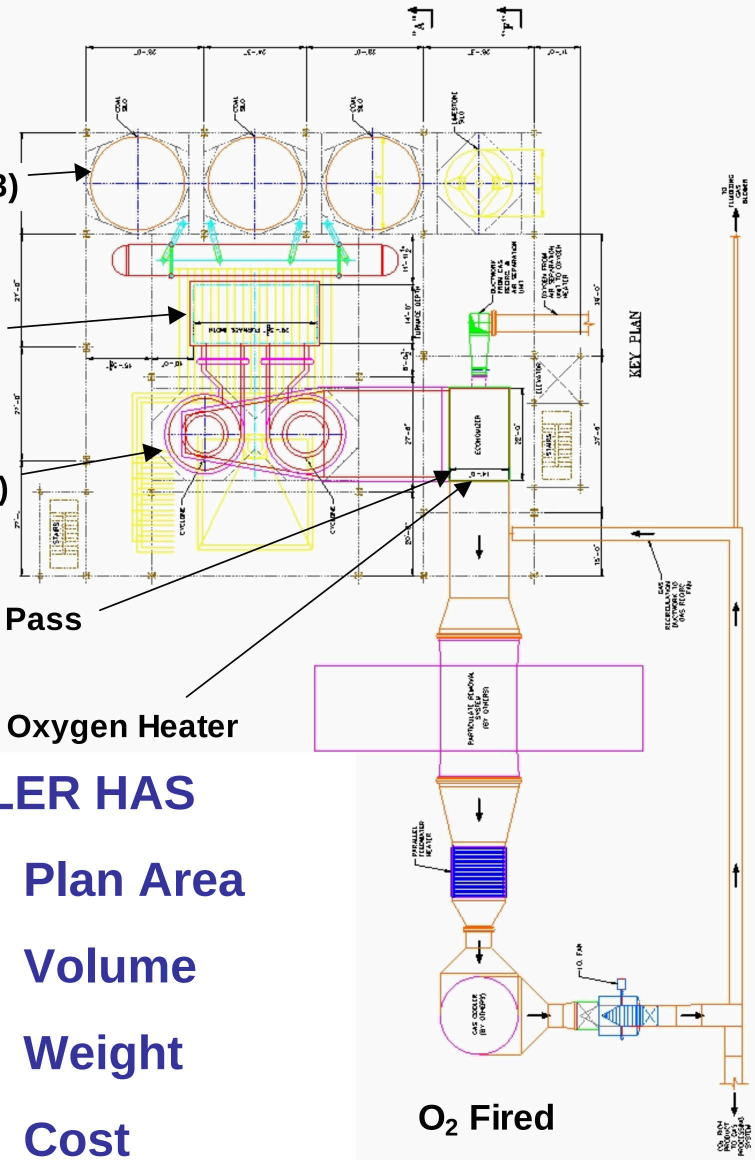
Comparison of plant layouts: 210 MWe Gross



Air Fired

O_2 BOILER HAS

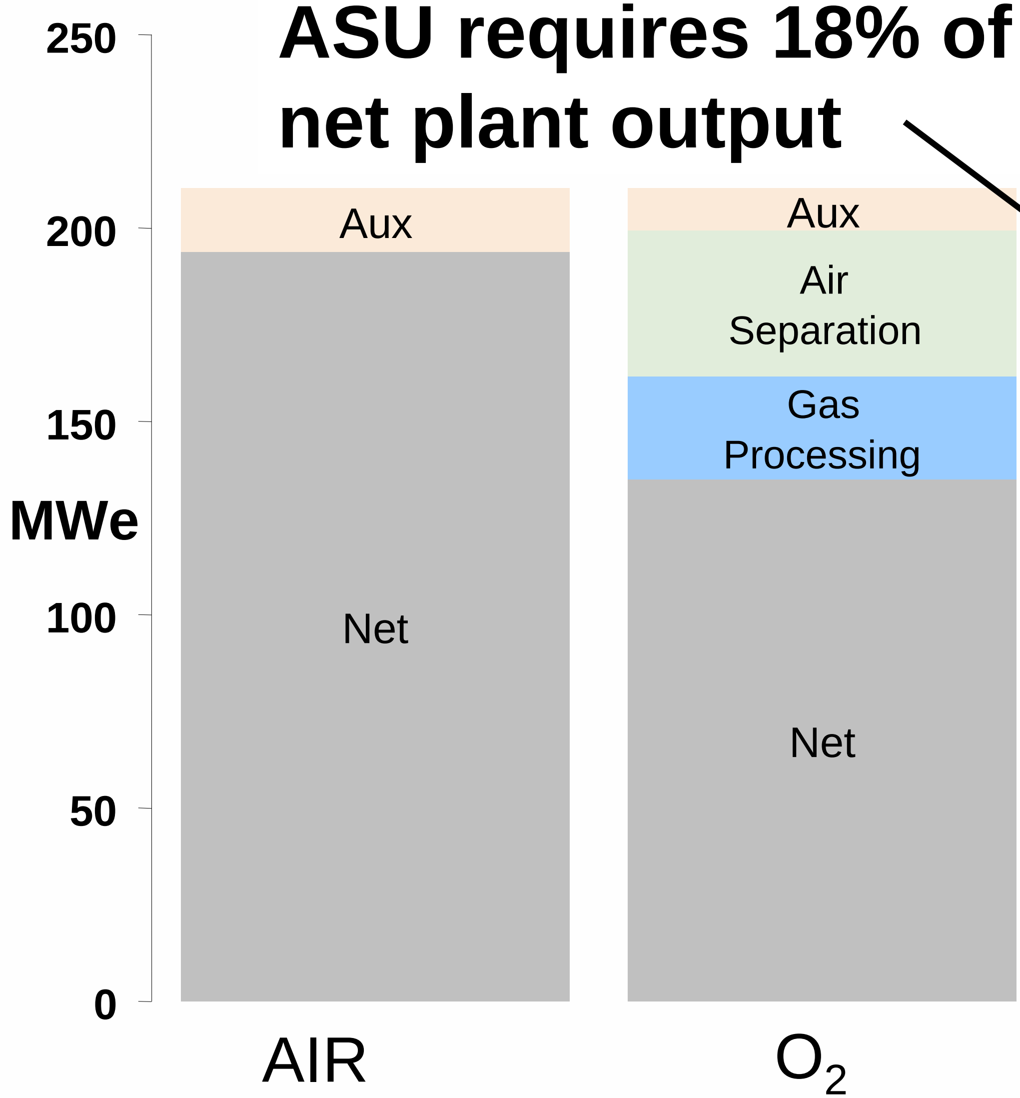
51%	Plan Area
56%	Volume
65%	Weight
68%	Cost



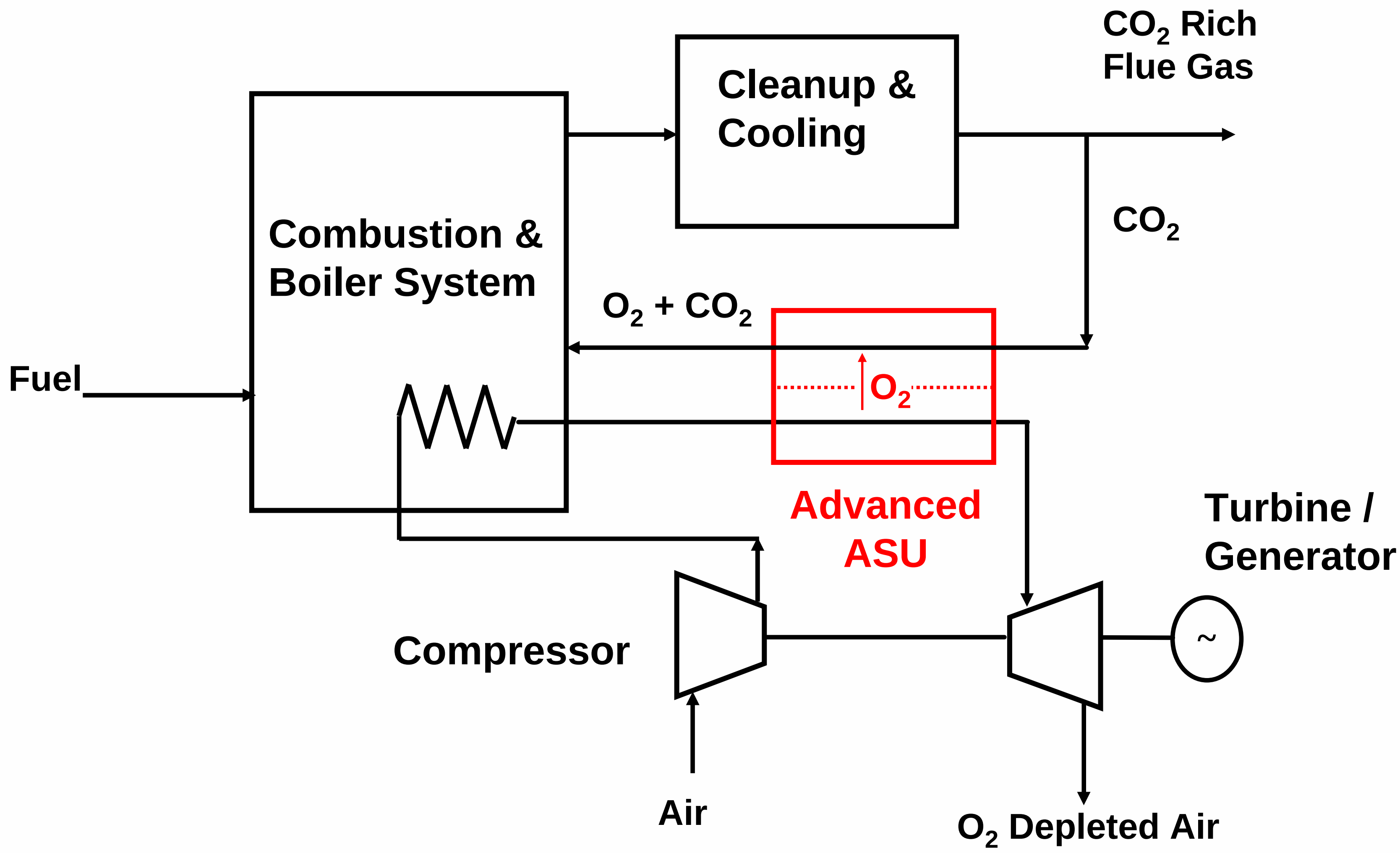
O_2 Fired

Comparison of plant power output: 210 MWe Gross

ASU requires 18% of net plant output

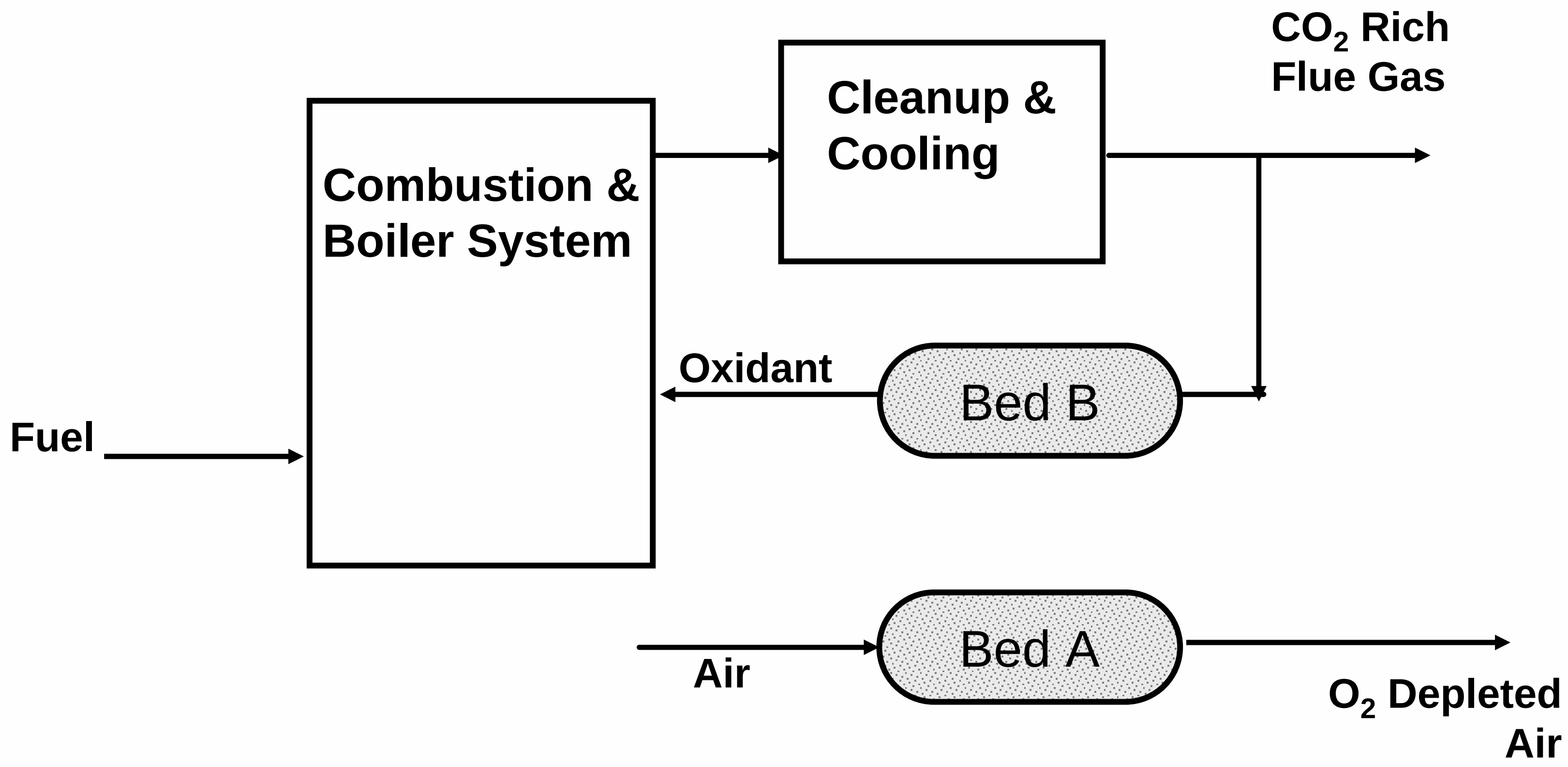


Advanced Oxygen Separation



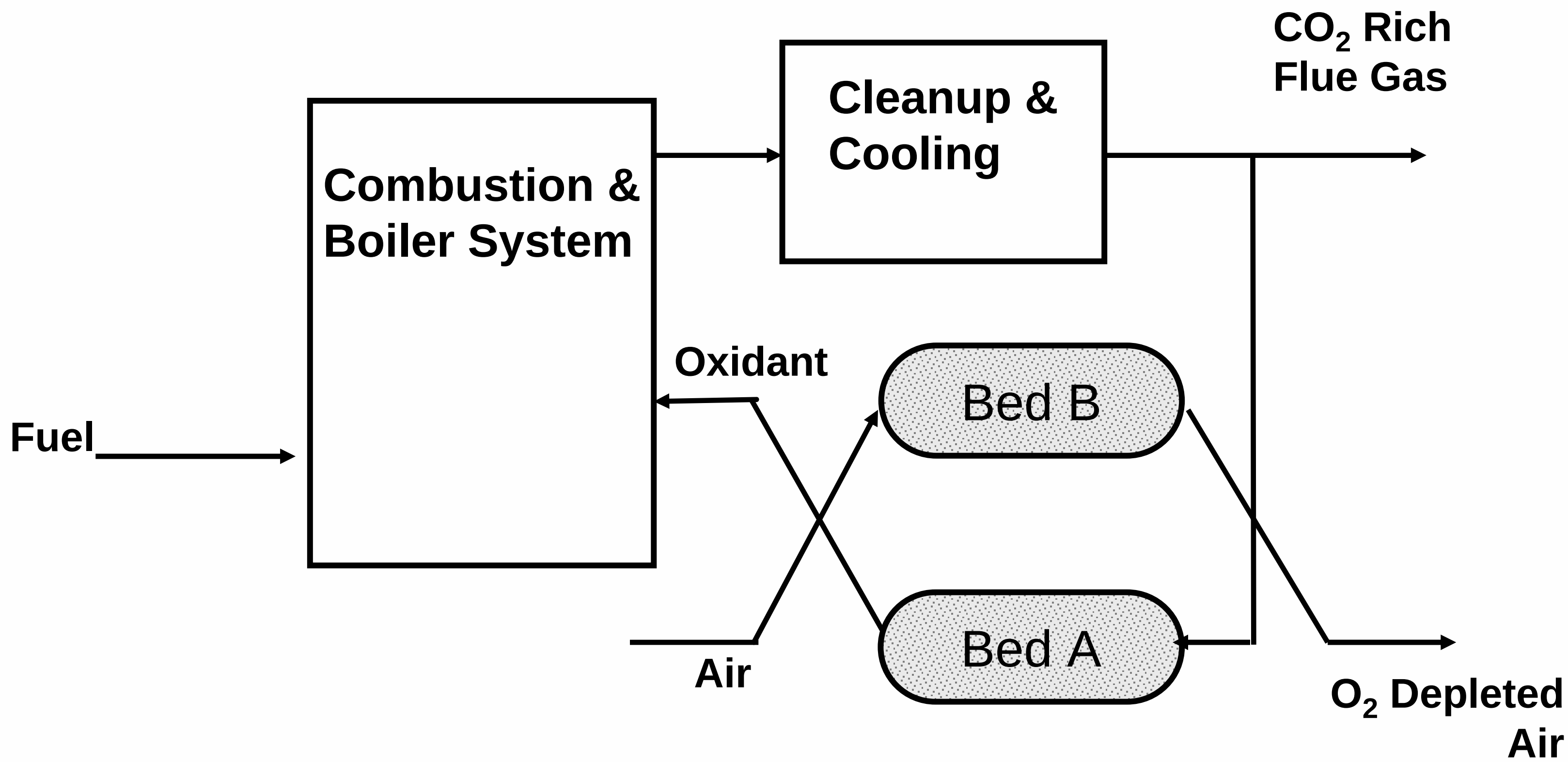
ALSTOM

Evaluation of Ceramic Autothermal Recovery



Perovskite materials have the capacity to absorb oxygen from air

Evaluation of Ceramic Autothermal Recovery



Cycle the valves to recharge Bed B while Bed A is used.

ALSTOM

Advanced *vs.* Cryogenic ASU

	AIR	CRYOGENIC ASU	ADVANCED ASU
Total Aux Power, % of Gross	8	36	20
Plant Efficiency, % HHV	35	25	30
Capital Cost*, $/kW	1300	2500	2400
COE*, ¢/kWh	4.5	8.0	7.0

Summary from DOE Phase I Study

* in 2003 dollars

ALSTOM Economic Studies

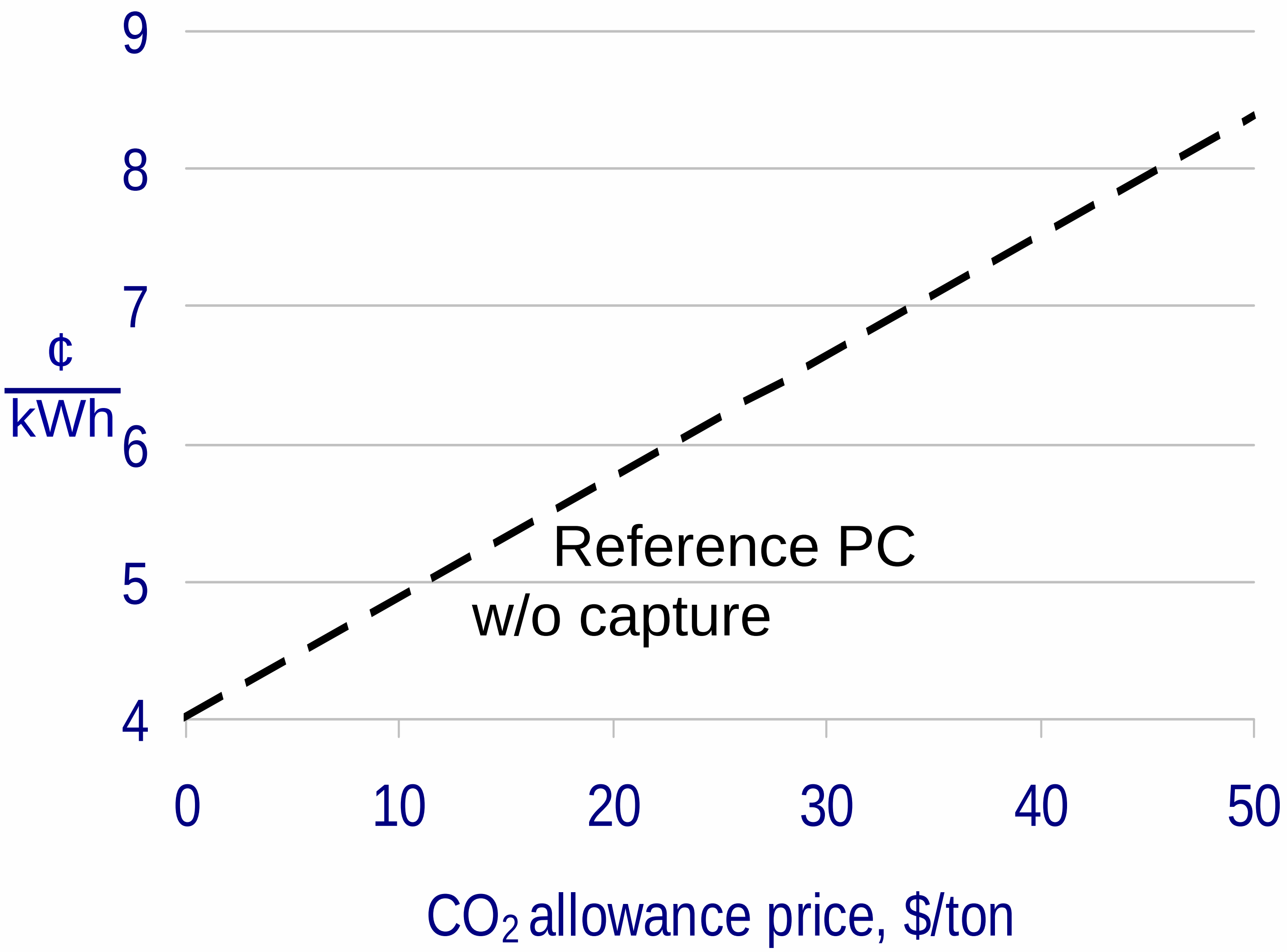
CO_2 Capture with Coal Power

ALSTOM CO_2 Capture for Power Studies:

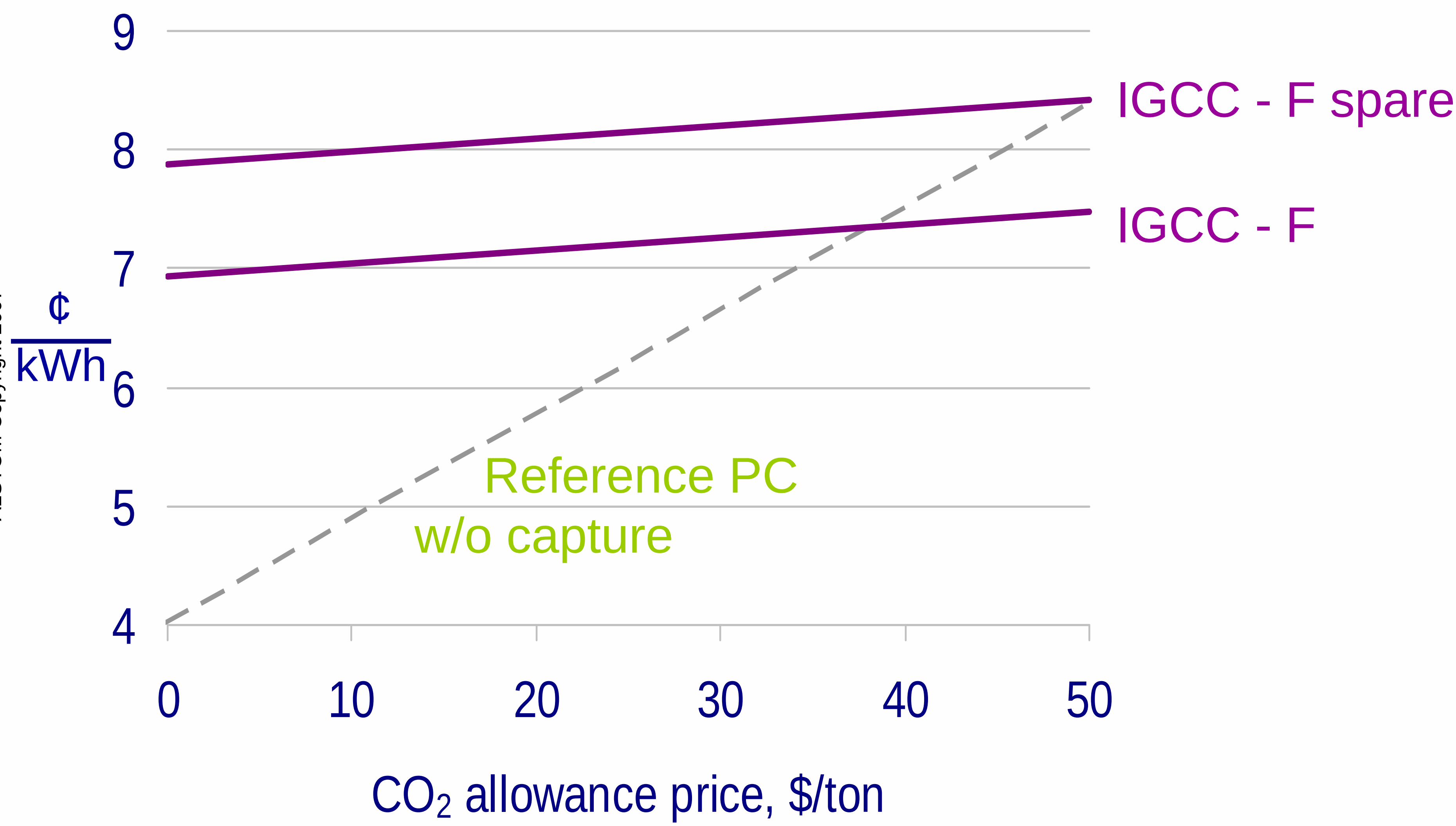
#	Project Name	Sponsors	Years
1	Technical Feasibility of a CO_2/O_2 Combustion Retrofit to an Existing Coal-Fired Boiler for CO_2 Extraction	ABB	1998
2	Preliminary Design and Costing of a CO_2/O_2 Combustion Retrofit to an Existing Coal-Fired Boiler for CO_2 Extraction	TransAlta Corp.	1999
3	Integration of Ceramic Oxygen Transport Membrane Processes with Coal Fired Power Plants	ABB	1999
4	CFB Boi Suncor		2000
5	CO_2 Ca Project f Sequestration		2000
6	CO_2 Capture in a Coal-Fired Boiler: Economic and Performance Sensitivity to CO_2 Capture Percentage for Amine-Based Processes	ALSTOM Power Inc.	2001
7	Engineering Feasibility and Economics of CO_2 Capture on an Existing Coal-Fired Power Plant	OCDO/DOE NETL	1999-2001
8	Greenhouse Gas Emissions Control by Oxygen Firing in Circulating Fluidized Bed Boilers	DOE NETL	2001-2004
9	GRACE - Chemical Looping Combustion - Feasability study	EU	2002 - 2003
10	CO2 capture (cascade cryogenics) - ECS/BUB	ADEME	2003 - 2004
11	CO2 Capture - Calcium cycle	ADEME	2003 - 2004
12	EDF - 2015	ADEME	2003 - 2005
13	ENCAP (Oxyfiring - Chemical Looping)	EU / IPFP6	2004
14	EnCap	EU	2003 - 2006

Fourteen economic studies from 1998 – 2006 with a variety of partners: DOE, EU and utilities

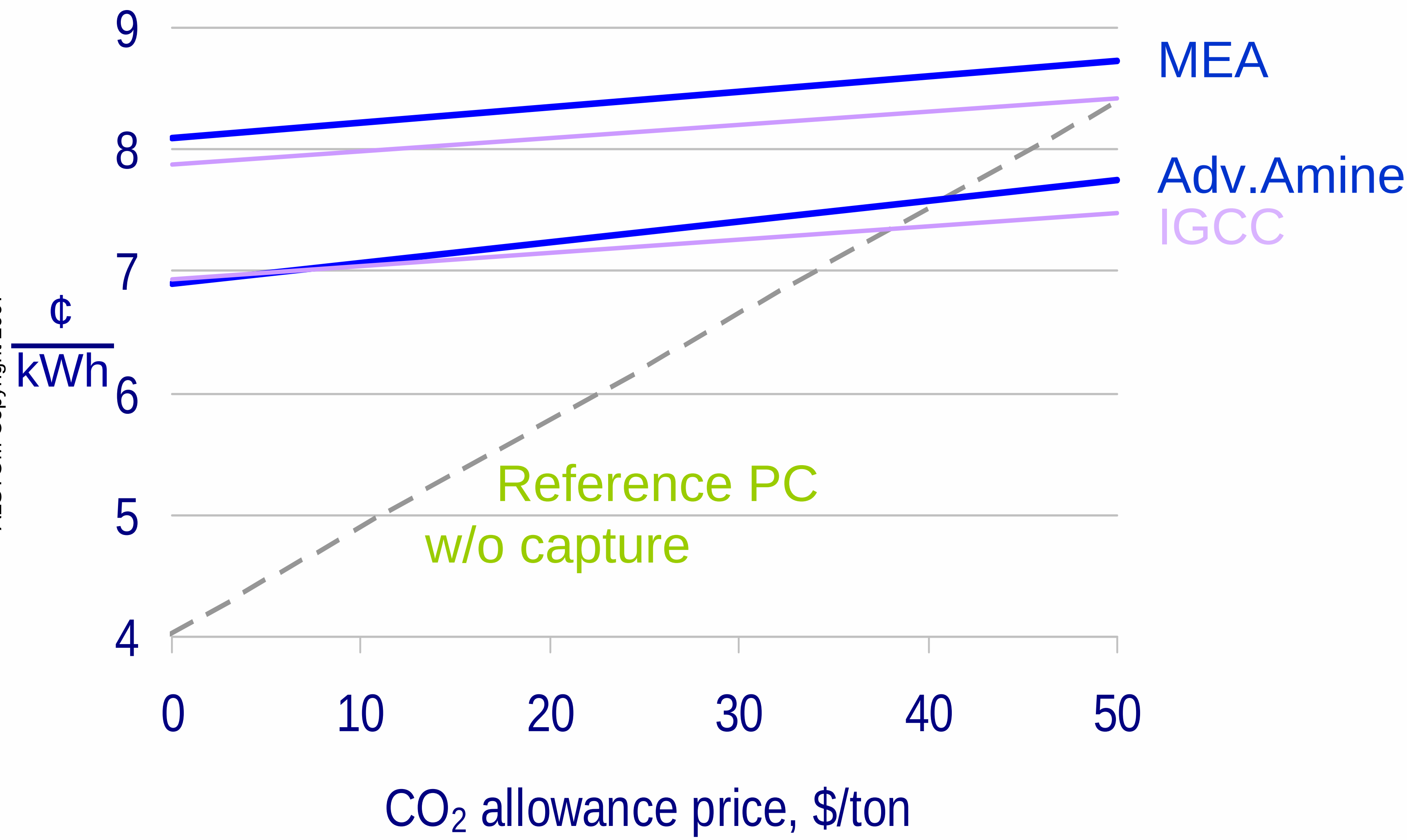
Levelized COE



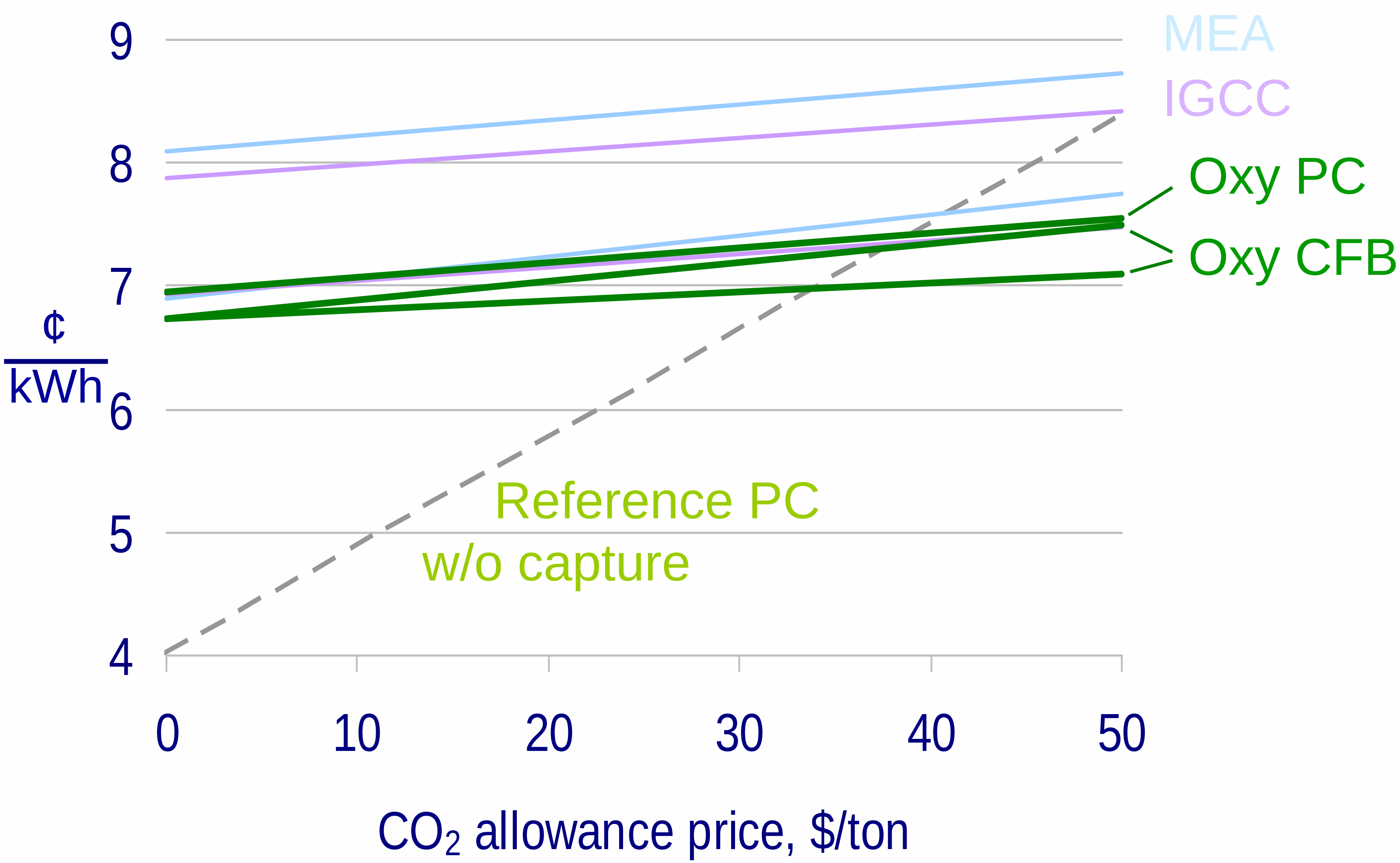
Levelized COE



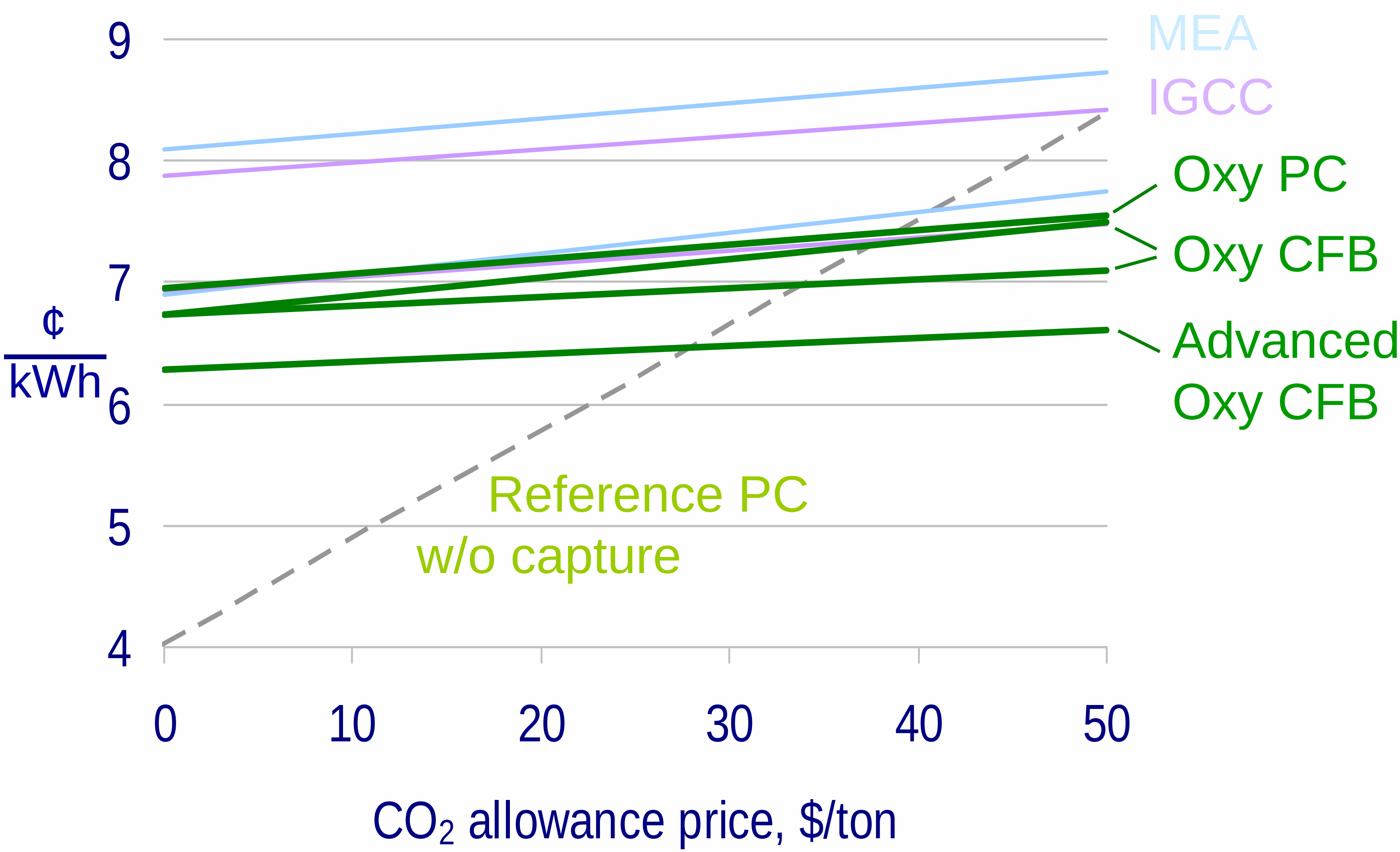
Levelized COE



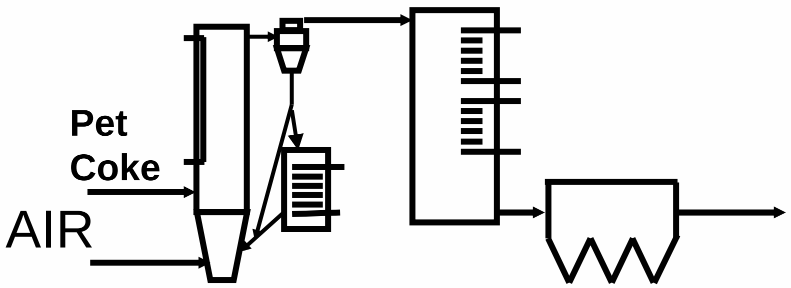
Levelized COE



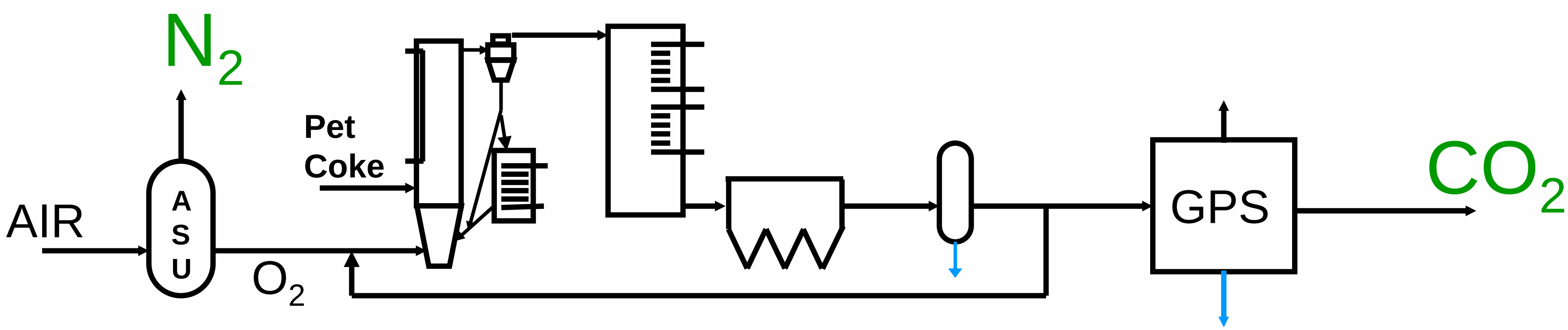
Levelized COE



CFB Greenfield/Retrofit for EOR



CFB Greenfield/Retrofit for EOR

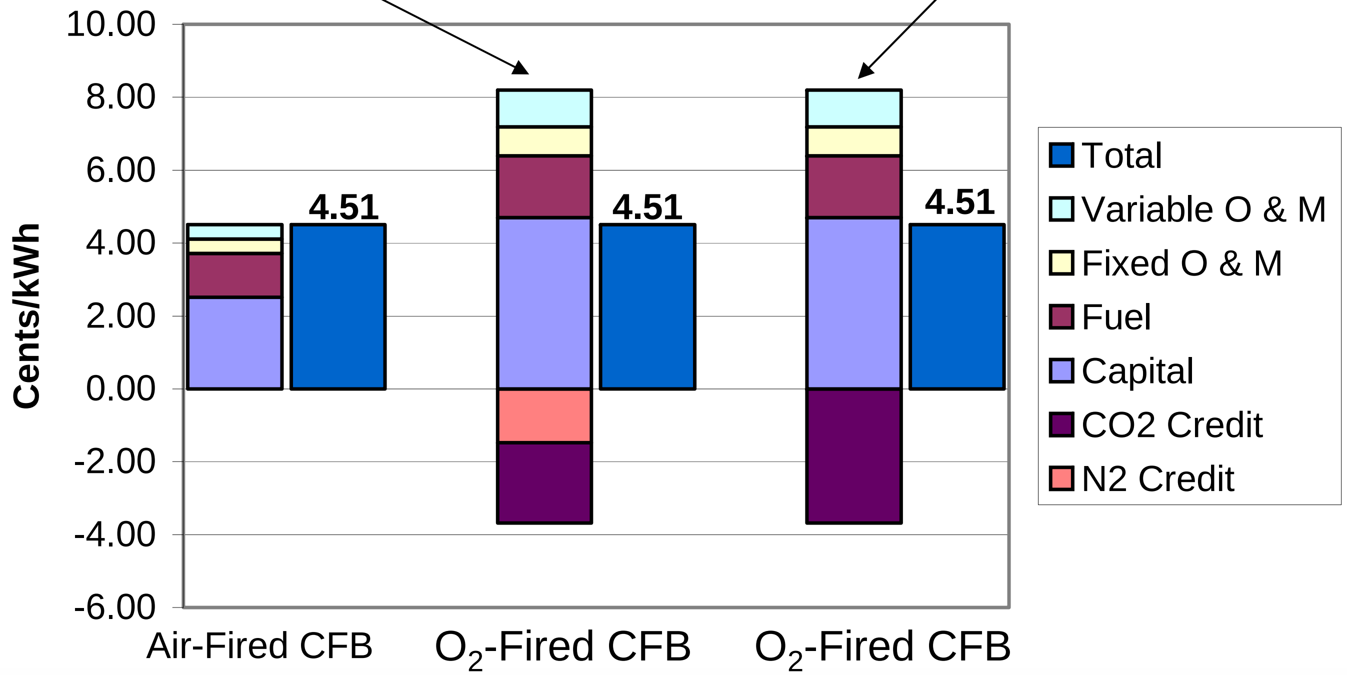


Use CO_2 and N_2 for Enhanced Oil Recovery

EOR Economics (210 MWe Gross, Greenfield)

Breakeven COE met with credits
- **CO_2 : 17 \$/ton**
- **N_2 : 4 \$/ton**

Breakeven COE met with credits
- **CO_2 : 28 \$/ton**



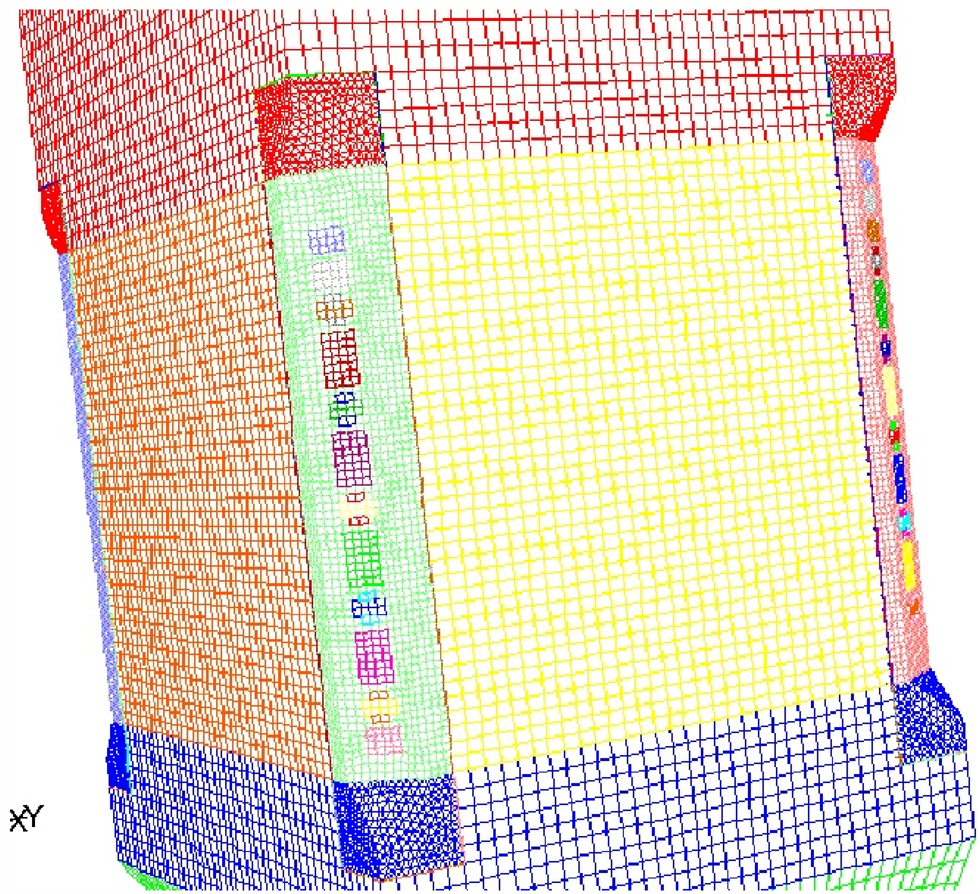
CFD as a tool to evaluate

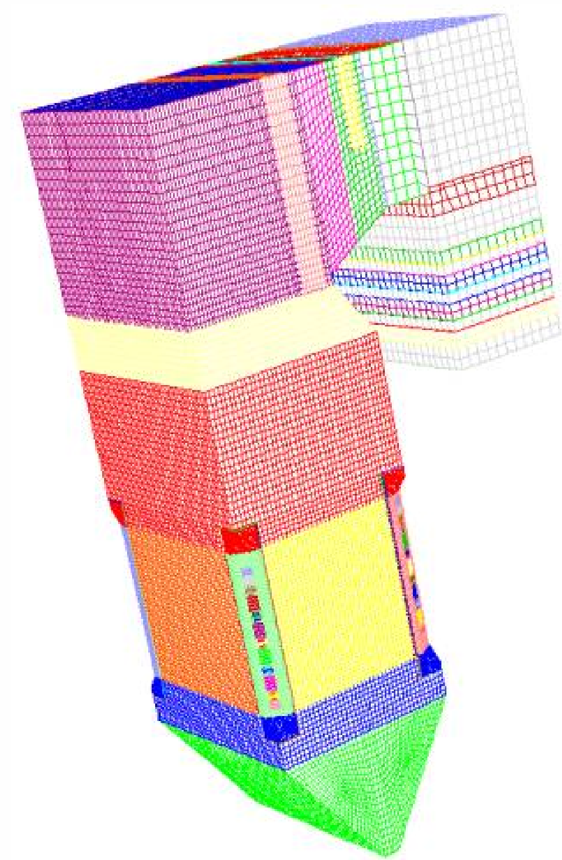
Oxy-firing

CFD Evaluation

- **Objective:** Simulation studies with Fluent™ of Conesville #5 to evaluate water-wall heat flux distribution and overall heat transfer in the furnace.
- **Approach:**
  - (1) Calibrate ALSTOM Power Inc.'s version of Fluent™ CFD code with a baseline Conesville #5 coal combustion case
  - (2) Use calibrated code to evaluate impact of the same coal combustion in various CO_2/O_2 ratios.
- **Outputs:**
  - **Relative radiation heat fluxes**
  - **Heat transfer**
  - **Furnace outlet temperature**
  - **Unburned carbon**
  - **NO_x emissions.**

Conesville #5: Base Case CFD Grid

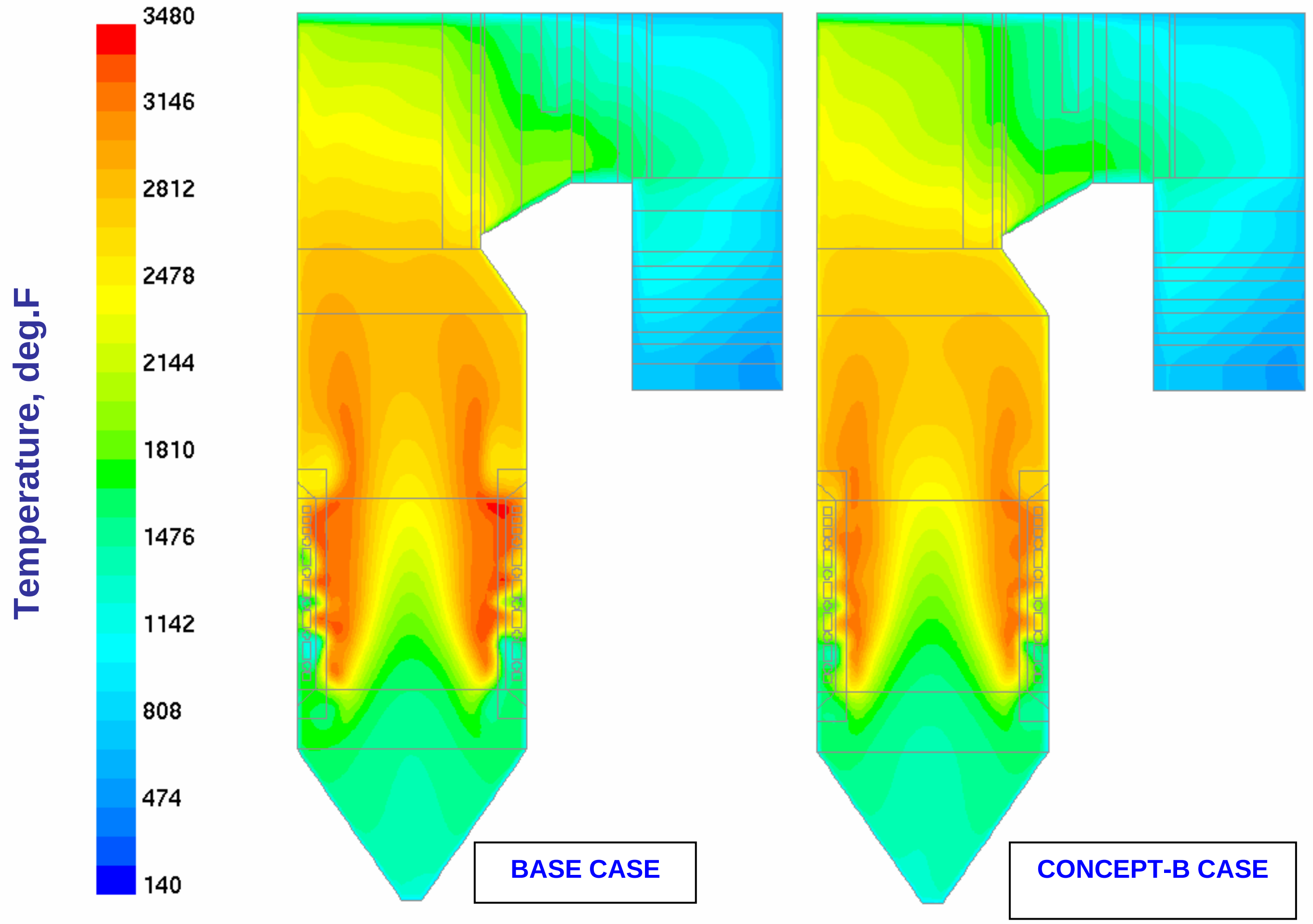




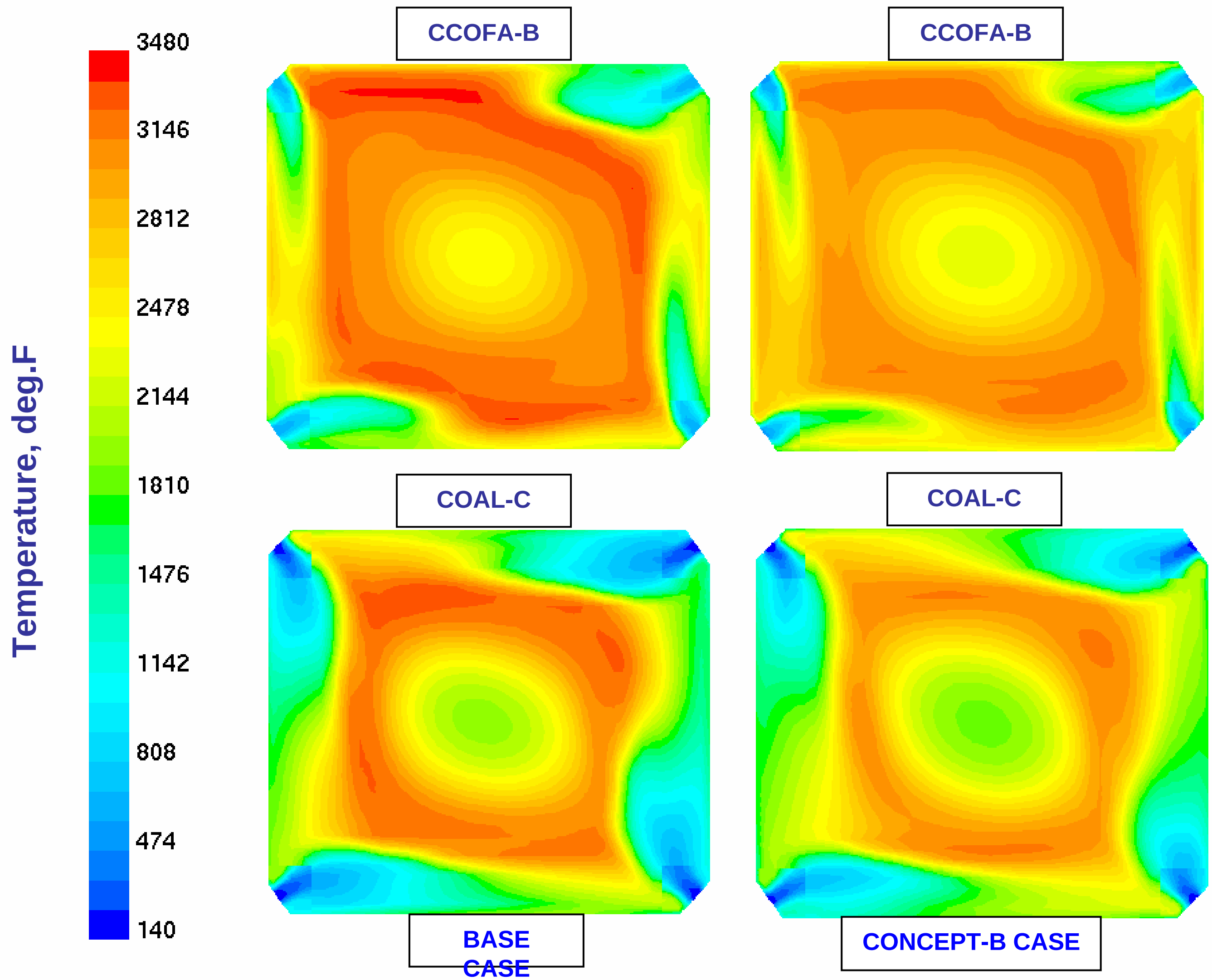
315,000 Cells (Unstructured Mesh)

ALSTOM

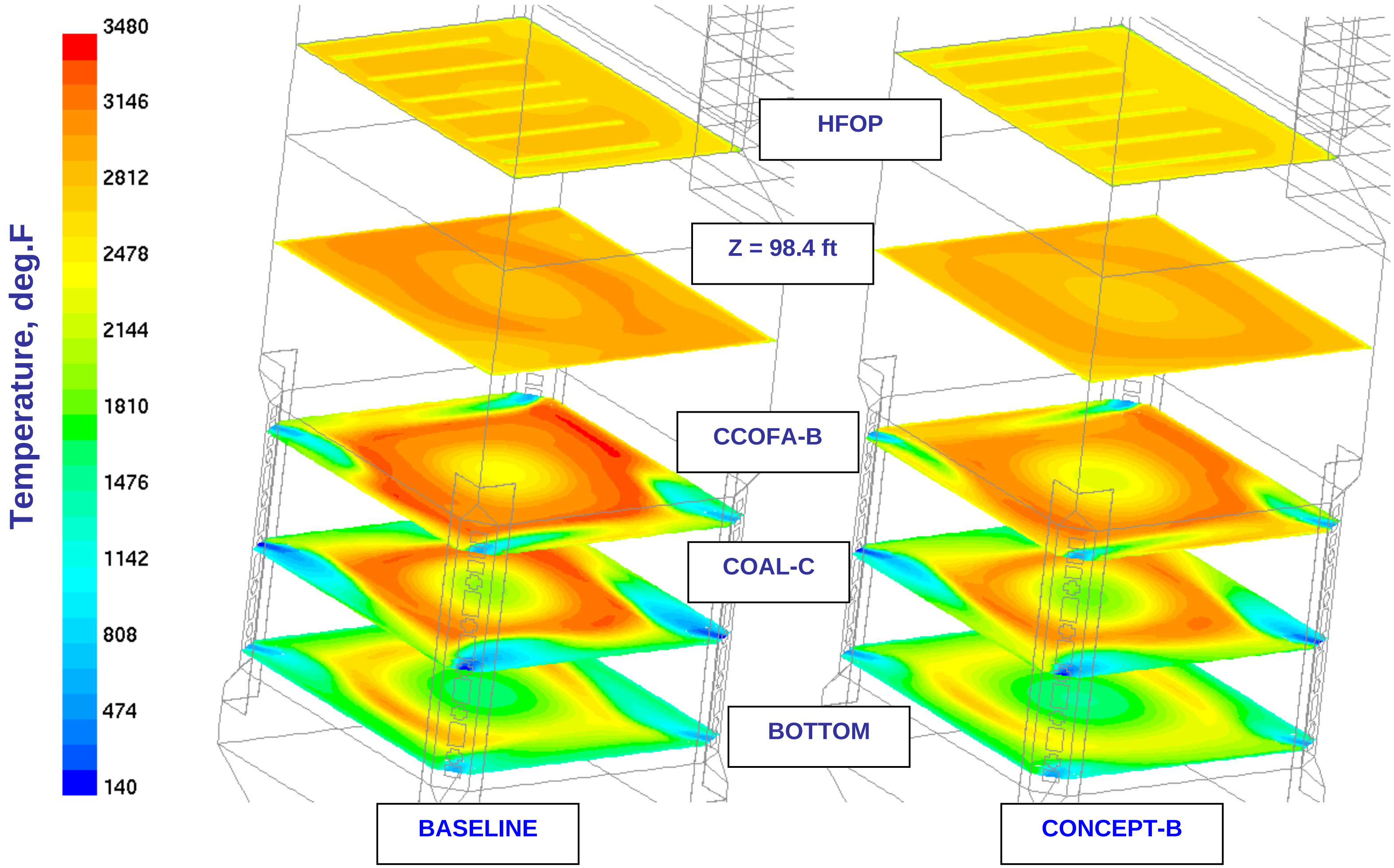
Conesville #5: Base Case Temperature Contours



Conesville #5: Temperature Contours



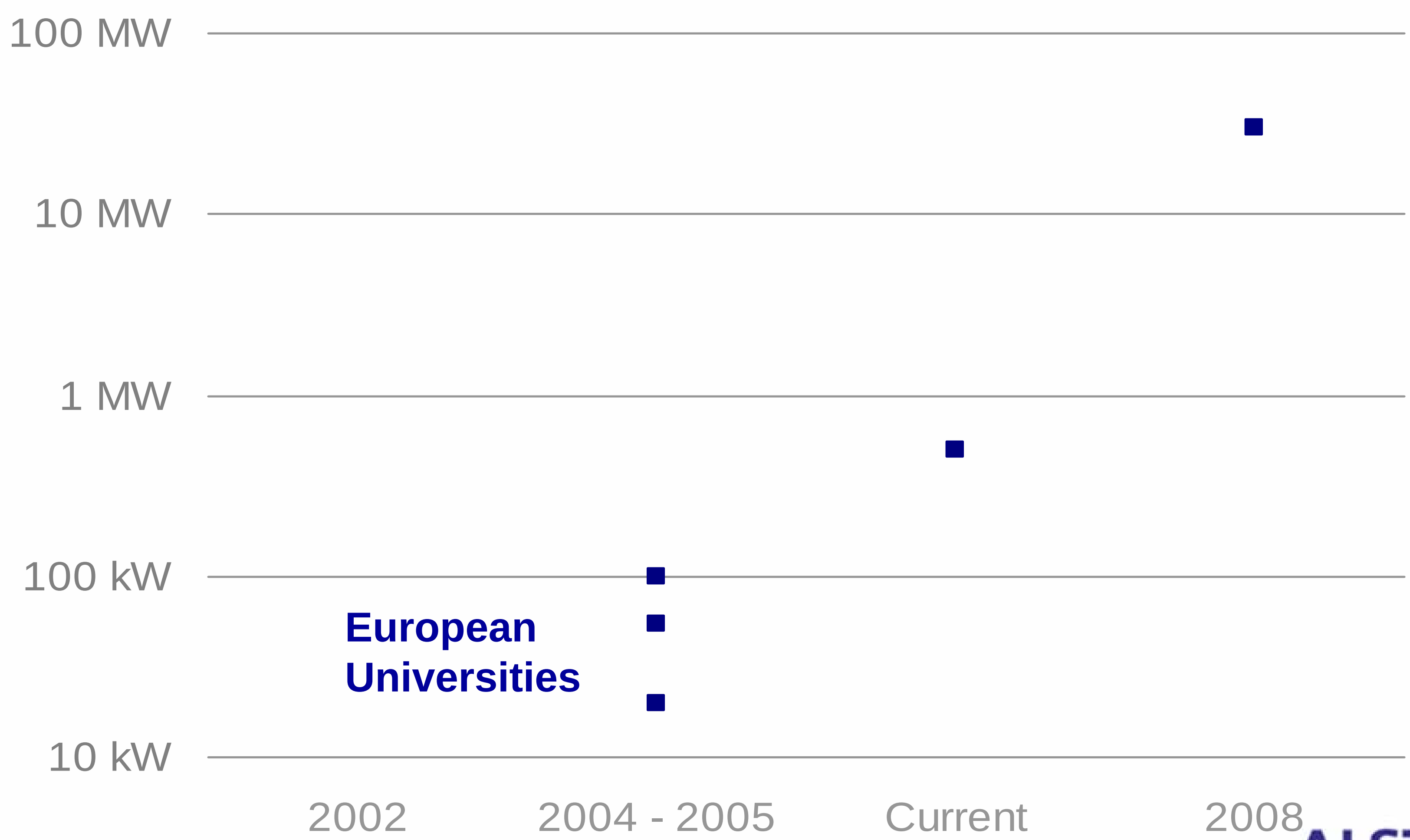
Conesville #5: Temperature Contours at elevations



ALSTOM Oxy-firing Testing

ALSTOM Oxyfuel Testing

PC Firing

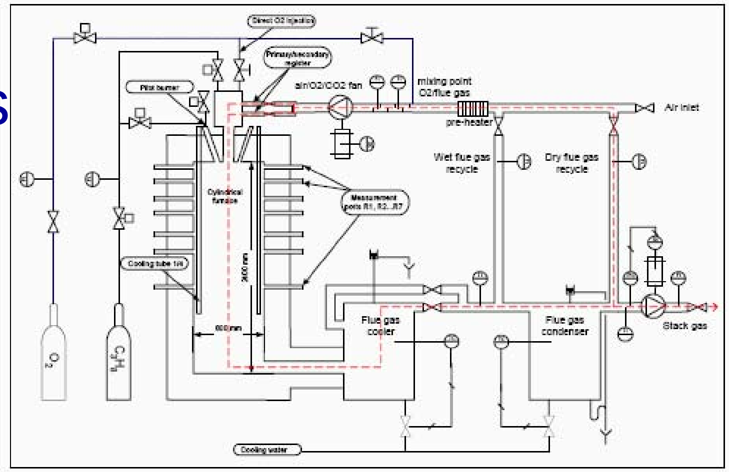


ALSTOM Oxyfuel Testing

Small Scale Test Results

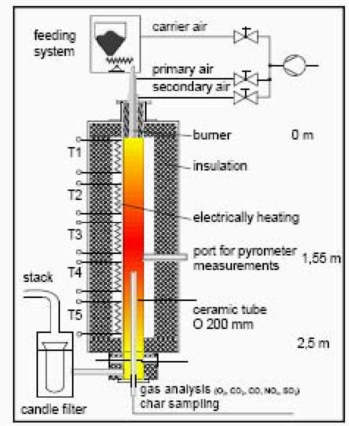
Test facilities in WP 3.1

- Gas Emissions
- Concentration Profiles
- Ignition and Burnout
- Ash Characterization
- Temperature Profiles
- Radiation Intensity



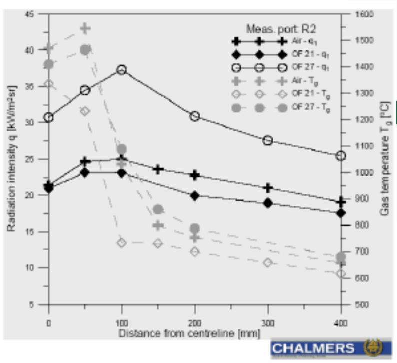
100 kW oxyfuel test rig at Chalmers

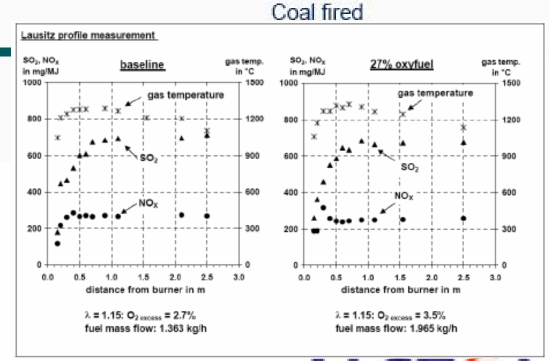
Gas and coal fired



20 kW test rig at U. Stuttgart

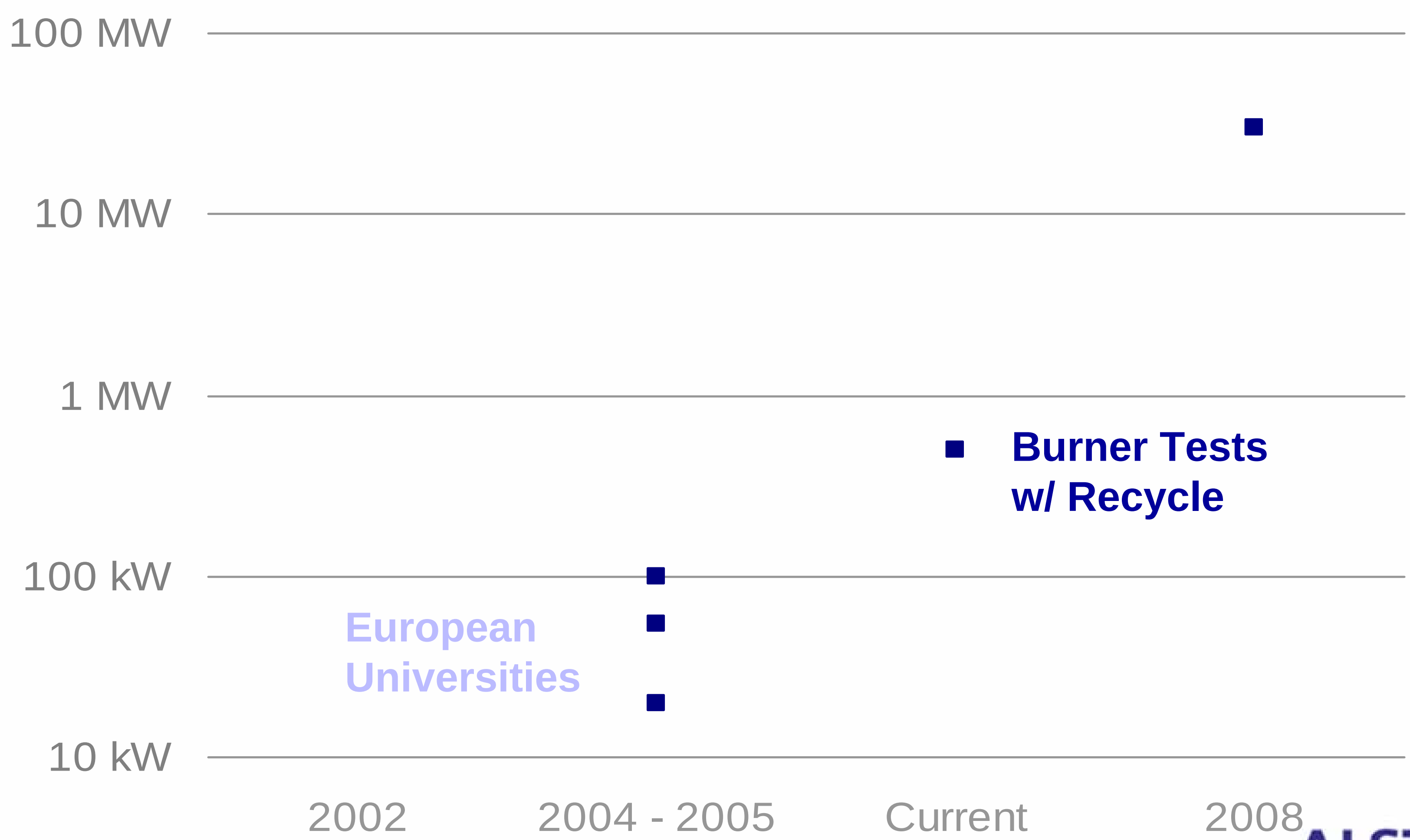
Coal fired





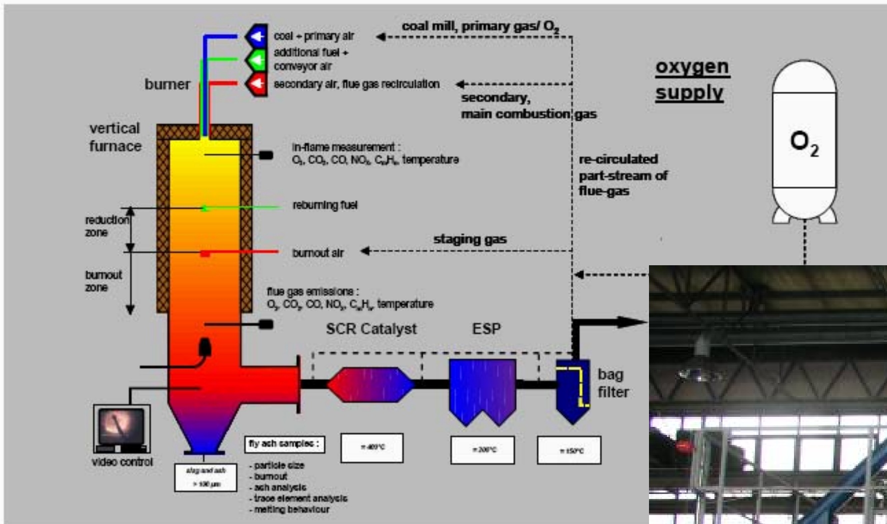
ALSTOM Oxyfuel Testing

PC Firing



ALSTOM Oxyfuel Testing

500 kW test facility at U. Stuttgart



encapco2

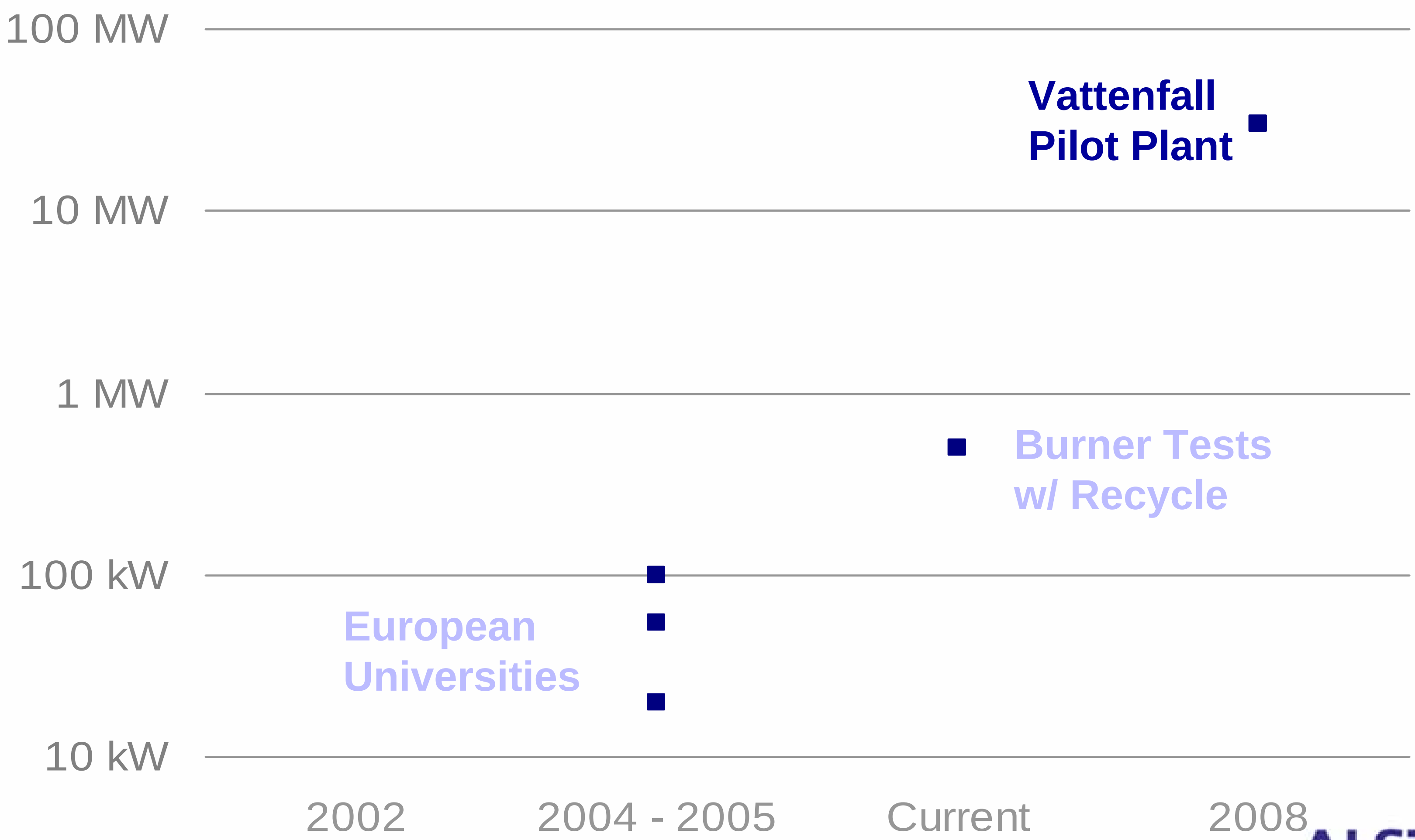
Burner Development with Flue Gas Recirculation

,

500 kW$_{th}$ at both Cottbus and Stuttgart Universities with ALSTOM participation

ALSTOM Oxyfuel Testing

PC Firing



Vattenfall 30 MW_{th} PC

Schwarze Pumpe Power Station

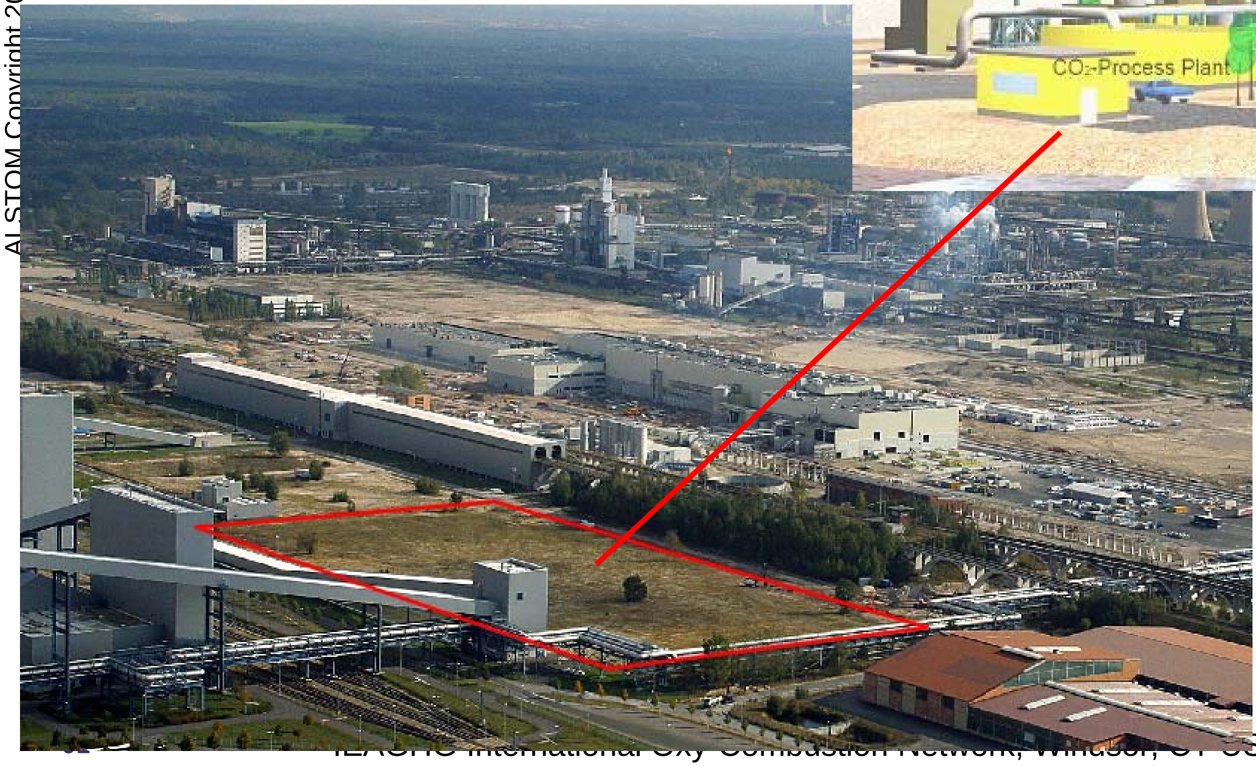
Brandenburg, Germany

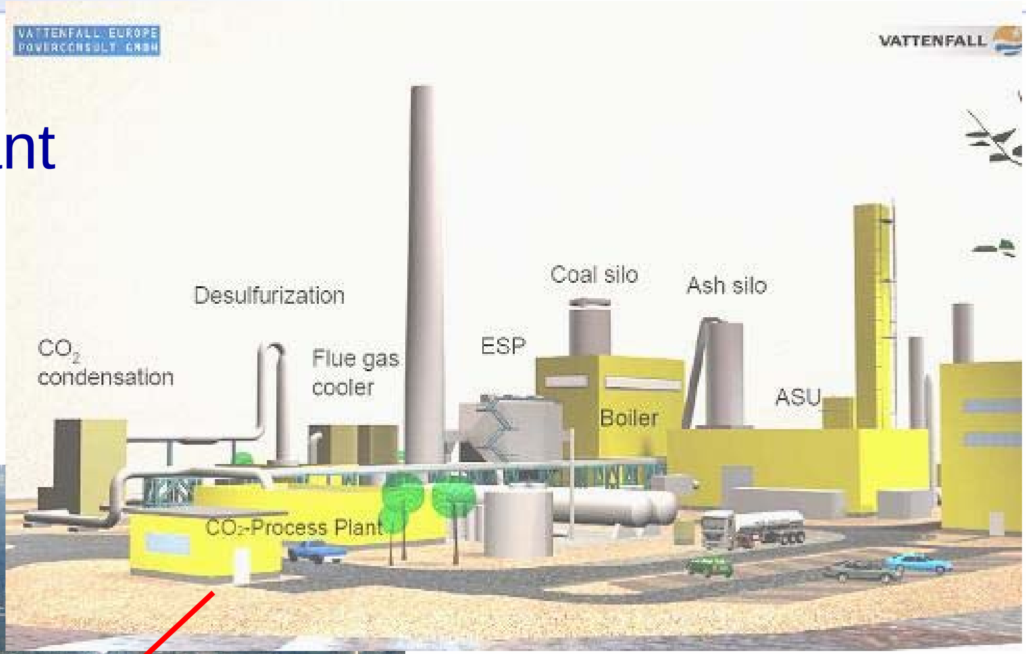
✌♌♍♎ is boiler and firing systems supplier

Vattenfall 30 MW_{th} PC

Complete Oxy-Fired Pilot Plant

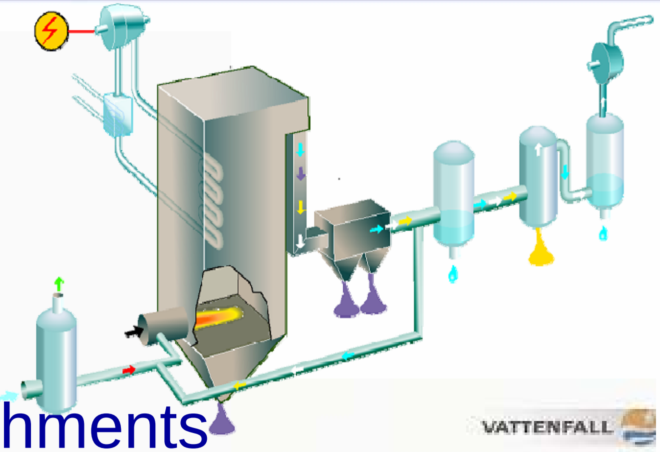
Startup in 2008

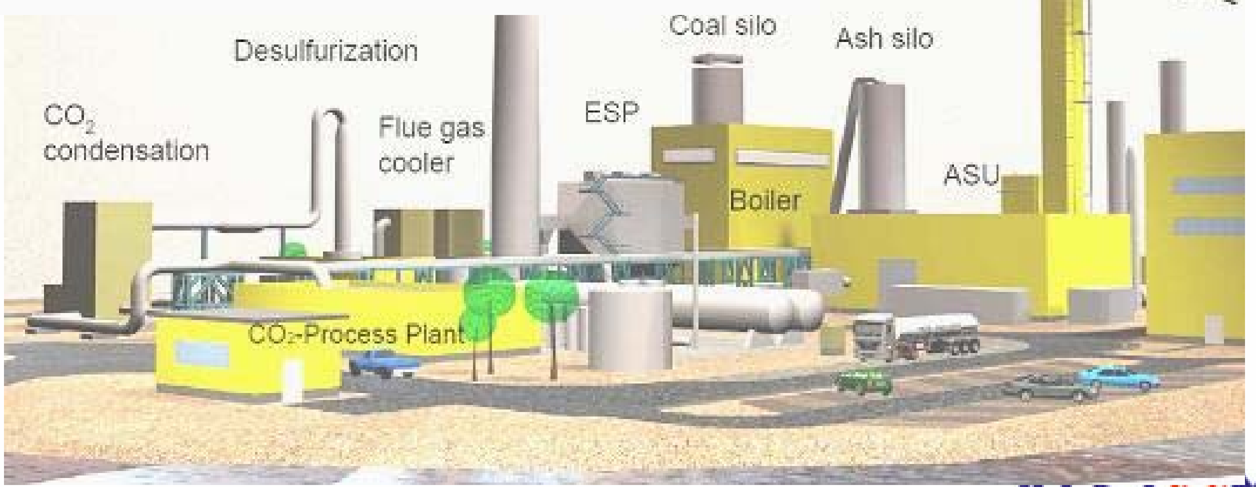




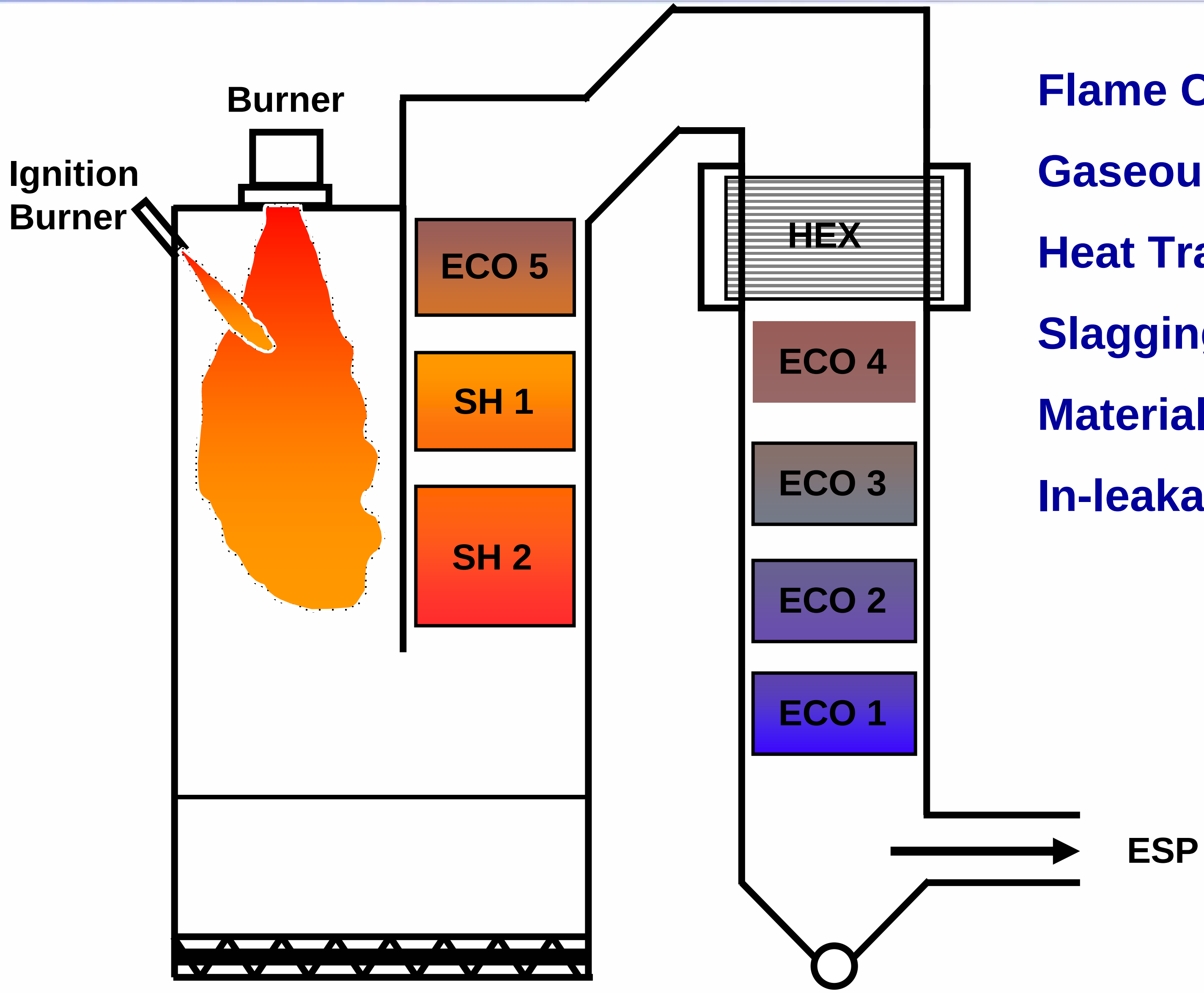
Vattenfall 30 MW_{th} PC

- Pre-Dried Lignite and Bituminous
- Air Blown Reference Operation
- 21-39% Overall Oxygen Enrichment
- Staged Combustion with Varying Enrichments
- Load Changes and Dynamic Interactions
- CO_2 Compression *vs.* Inert Levels





Vattenfall 30 MW_{th} PC



Flame Characteristics

Gaseous Emissions

Heat Transfer

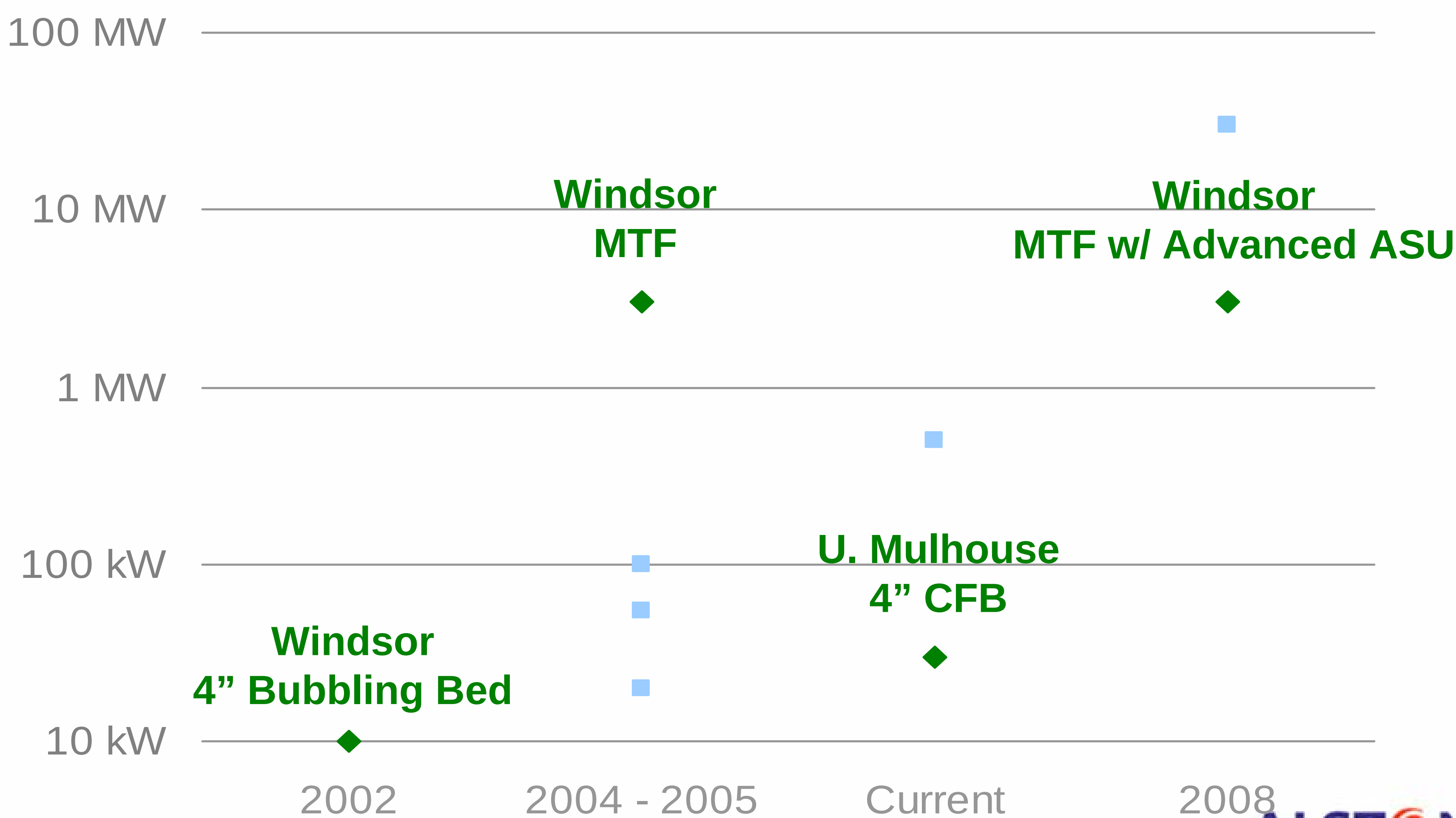
Slagging and Fouling

Materials Analysis

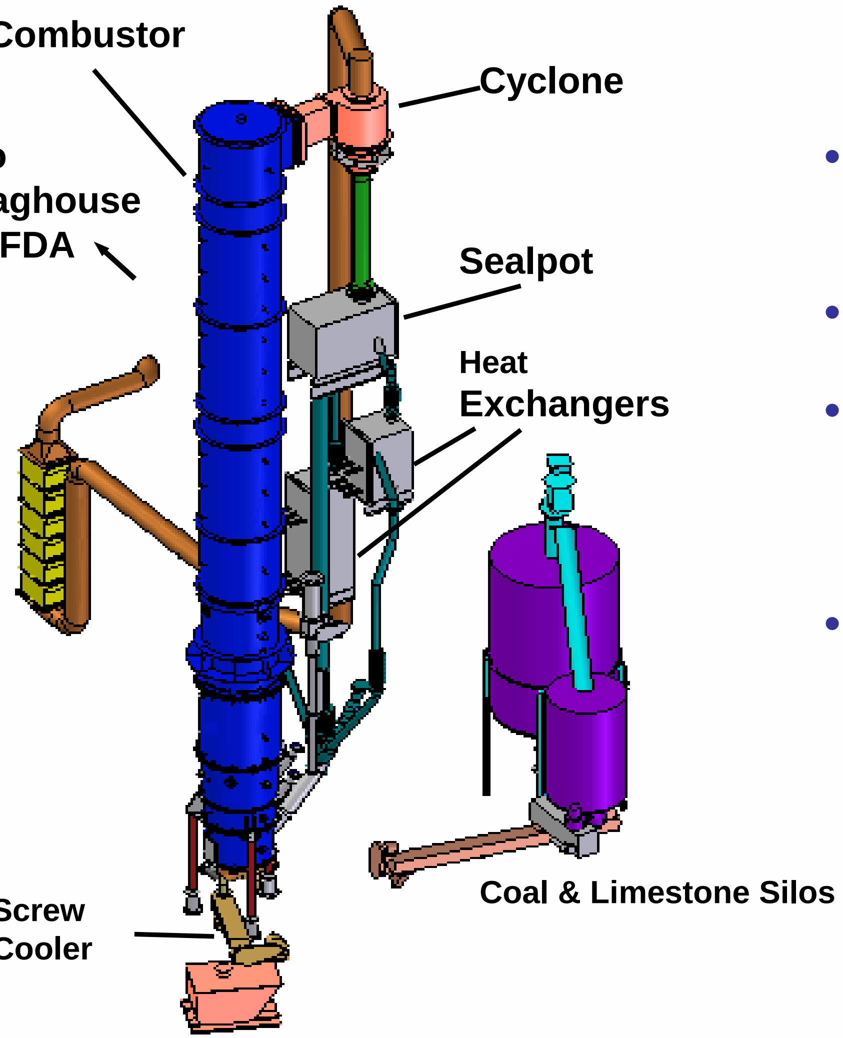
In-leakage

ALSTOM Oxyfuel Testing

Fluidized Bed

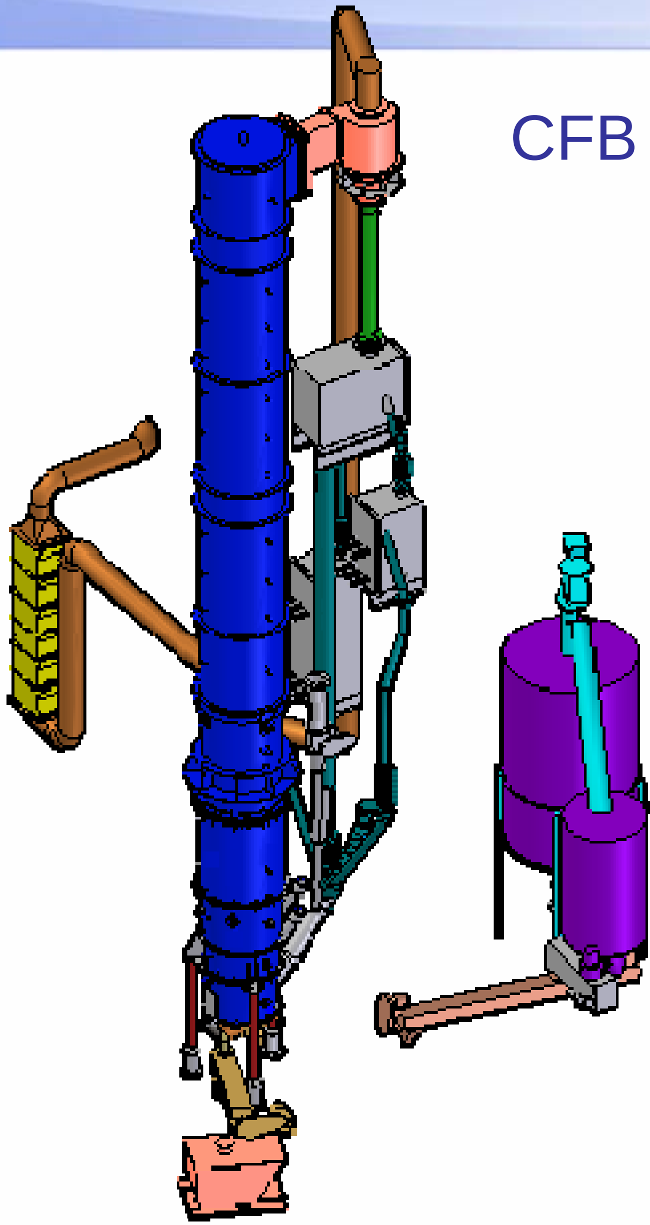


3 MWth Multiuse Test Facility



- **MTF Located at Power Plant Labs**
  Windsor, Connecticut
- **9.9 MM-Btu/hr (2.9 MW_{th})**
- **Furnace:**
  60 feet (18 m) tall
  40 inch (1 m) I.D.
- **42 Test Campaigns since 1998**

3 MWth Multiuse Test Facility



CFB Modified for Oxygen firing in 2004 & 2005

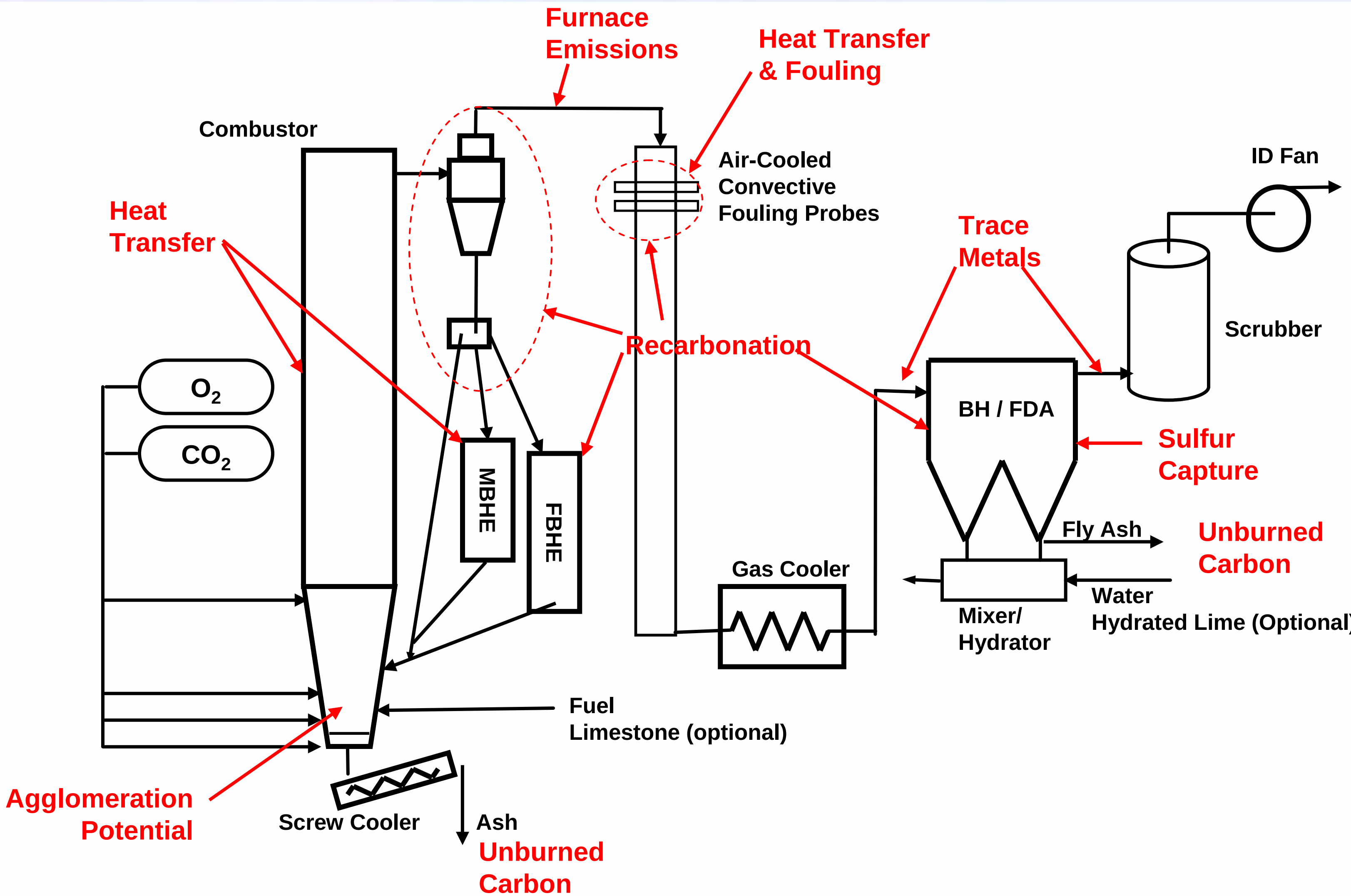
Summary of Concept Validation/Testing – DOE Greenhouse Gas Program

Year	April 2004	June 2004	June 2005
Fuel	Medium Volatile Bituminous Coal	Medium Volatile Bituminous Coal and Petcoke	Medium Volatile Bituminous Coal and Petcoke
Sorbent	Limestone	Aragonite	Lime Limestone Aragonite
Firing Rate	2.2 - 4.8 MM-Btu/hr (0.64 – 1.41 MW_{th})	4.2 - 7.9 MM-Btu/hr (1.23 – 2.32 MW_{th})	9.9 MM-Btu/hr (2.9 MW_{th})
Combustion Medium	Air and 20 - 30% O_2 CO_2 Balance	40 - 50% O_2 CO_2 Balance	Air and 30% O_2 70 % CO_2 Balance

Two fuels and three sorbents evaluated in air and O_2/CO_2 mixtures of up to 70% O_2 (by vol.)

ALSTOM

Issues Addressed



Test Results: no show stoppers

- Heat transfer as expected
- No bed agglomeration
- Emissions (SOx, NOx, CO HC and trace monitored)
- NOx lower
- CO somewhat higher

…. Next Steps

- **Future**
  - **Oxyfiring**
    - **ALSTOM plans to demo PC/CFB technologies**
    - **Vattenfall a 200 MWe PC by 2015**
    - **ALSTOM scaling CFB technology for demo**
  - **Post combustion technologies**
    - **Ammonia scrubbing**

- **Conclusion**
  - **Oxy-firing is a relatively near term and cost competitive approach built on current technology**

www.alstom.com

Windsor, 25th of January, 2007

Combustion Tests and Modeling of the Oxy-Fuel Process – An Overview of Research Activities at Chalmers University

KLAS ANDERSSON

Department of Energy and Environment, Chalmers University of Technology

The oxy-fuel group at Chalmers consists of 7 researchers at the dept. of Energy and Environment:

- Prof. Filip Johnsson
- Prof. Bo Leckner
- Associate Prof. Henrik Thunman
- PhD cand. Stefan Hjärtstam (CFD modeling & experiments)
- PhD cand. Robert Johansson (Heat transfer modeling)
- PhD cand. Fredrik Normann (Chemistry modeling)
- PhD cand. Klas Andersson (Experiments and heat transfer modeling)

Experimental and combustion modeling work performed in various projects

- Close collaboration with Vattenfall, FLUENT and IVD/Uni-Stuttgart, AGA/Linde and DOOSAN/Mitsui Babcock etc.

The focus of the Chalmers group is on the combustion fundamentals of the process – for gas and coal-firing so far

- Combustion chemistry
- Heat transfer
- Fluid mechanics

- Both gas- and coal-fired experiments required in CFD model development – SCALING
- The combustion tests comprise:

  → **Propane fired tests:** to identify and characterize **differences in flame properties** between oxy-fuel and air combustion conditions

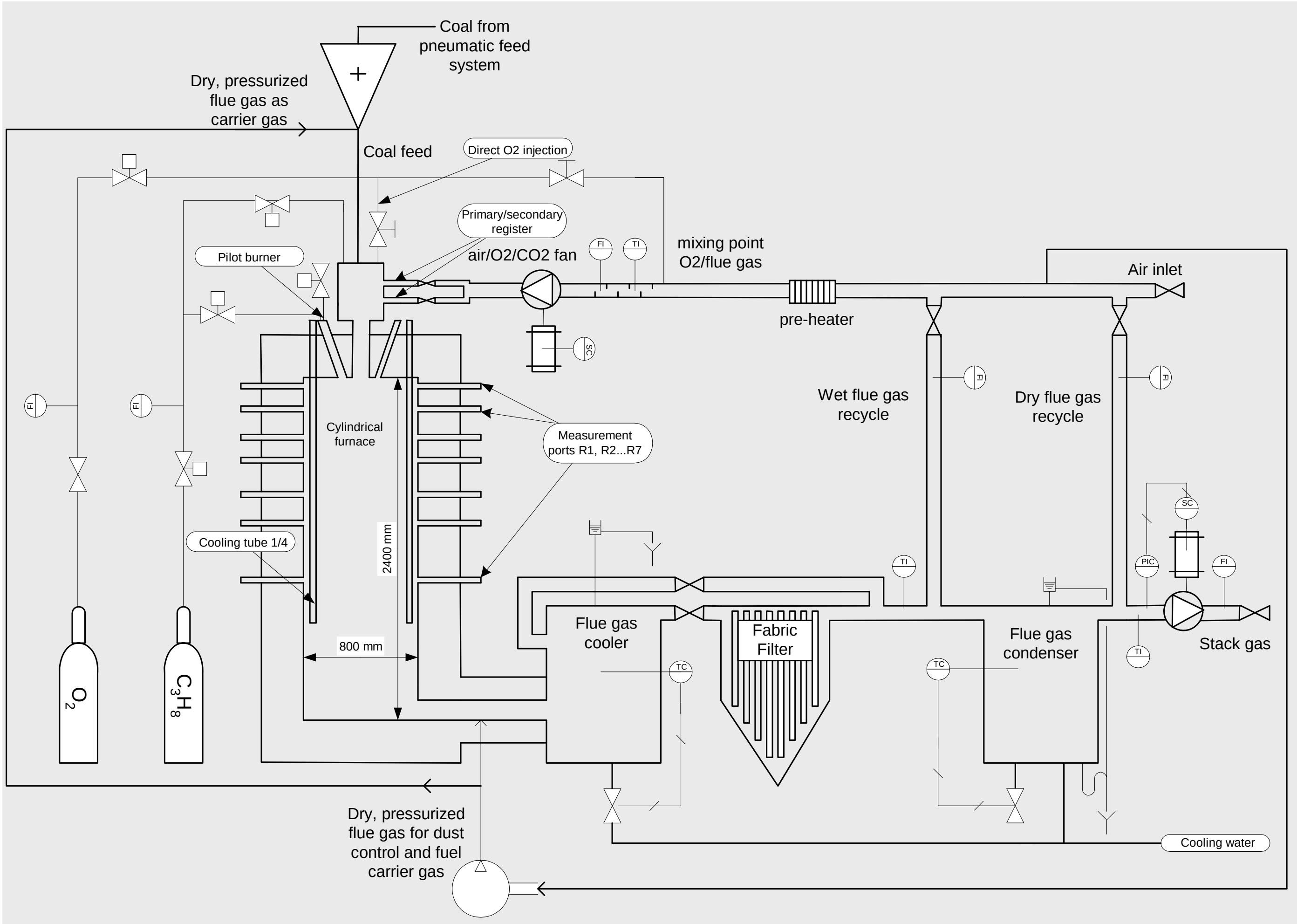
  → Emphasize put on the difference in radiation characteristics, without the influence from particles and ash

  → **Lignite fired tests:** to evaluate the combustion fundamentals of lignite-fired flames in air and various O_2/CO_2 environments

  → Focus on combustion chemistry and heat transfer/radiation

CHALMERS 100 kW_{th} oxy-fuel test facility

100 kW_{th} test unit
- -Gas-firing
- -Coal-firing
- -Oxygen enriched combustion (separate lance)

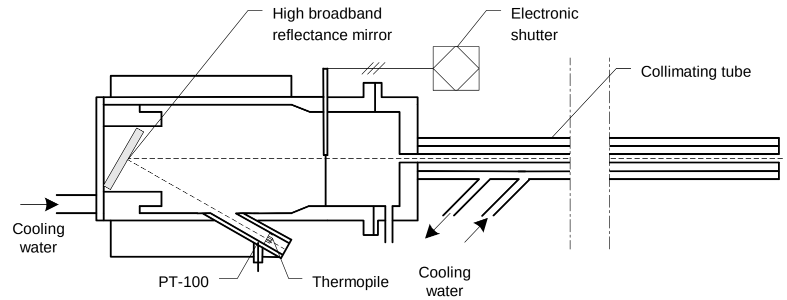


Combustor:
- Di = 0.8m
- H = 2.4 m
- Refractory lined
- 7 x 4 meas ports
- optical access

RESULTS FROM GAS-FIRED TESTS

Test conditions and measurements during Gas-fired tests

- **In-furnace measurents:**
  - gas composition
  - Temperature
  - Radiation intensity profiles
  - Velocity profiles (@STP)



Fuel input	80 kWth	Fuel		C_3H_8	Stoich ratio	1.15
Primary register	Fin angle	Swirl No		Secondary register	Fin angle	Swirl No
	45	0.79			15	0.21

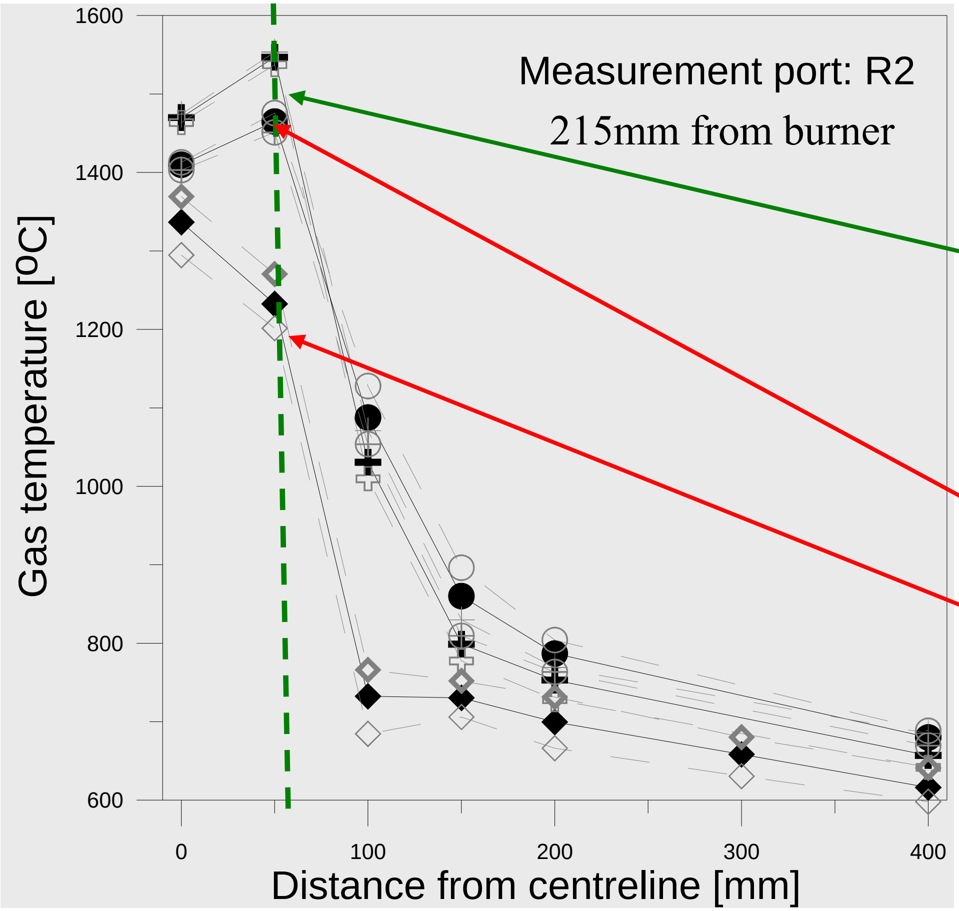
Test case	Combustion media	Temp feed gas [°C]	Feed gas composition (vol %)			Theoretic CO_2 conc. @ stack (vol %)
			O_2	N_2	CO_2	
Air	air	25-30	21	79	-	12
OF21	O2/CO2 dry recycle	25-30	21	-	78	96
OF27	O2/CO2 dry recycle	25-30	27	-	72	95

Flame emission from propane-flames, 215 mm from burner inlet

- **The flame emission changes significantly for different oxy-fuel conditions**
- **This effect is caused by different rates of soot formation, which is affected by the CO_2 (and recycle rate) through the following mechanisms**
  - Thermal effects (soot formation is dependant on temperature)
  - Chemical effects from CO_2 (The CO oxidize soot-precursors)
  - Dispersion (The conc. of soot precursors, e.g. acethylene, vary with RR)

Air-firing, $\lambda = 1.15$ Oxy-fuel, OF 21, $\lambda = 1.15$ Oxy-fuel, OF 35, $\lambda = 1.40$

Radial temperature profiles: 215 mm from burner inlet

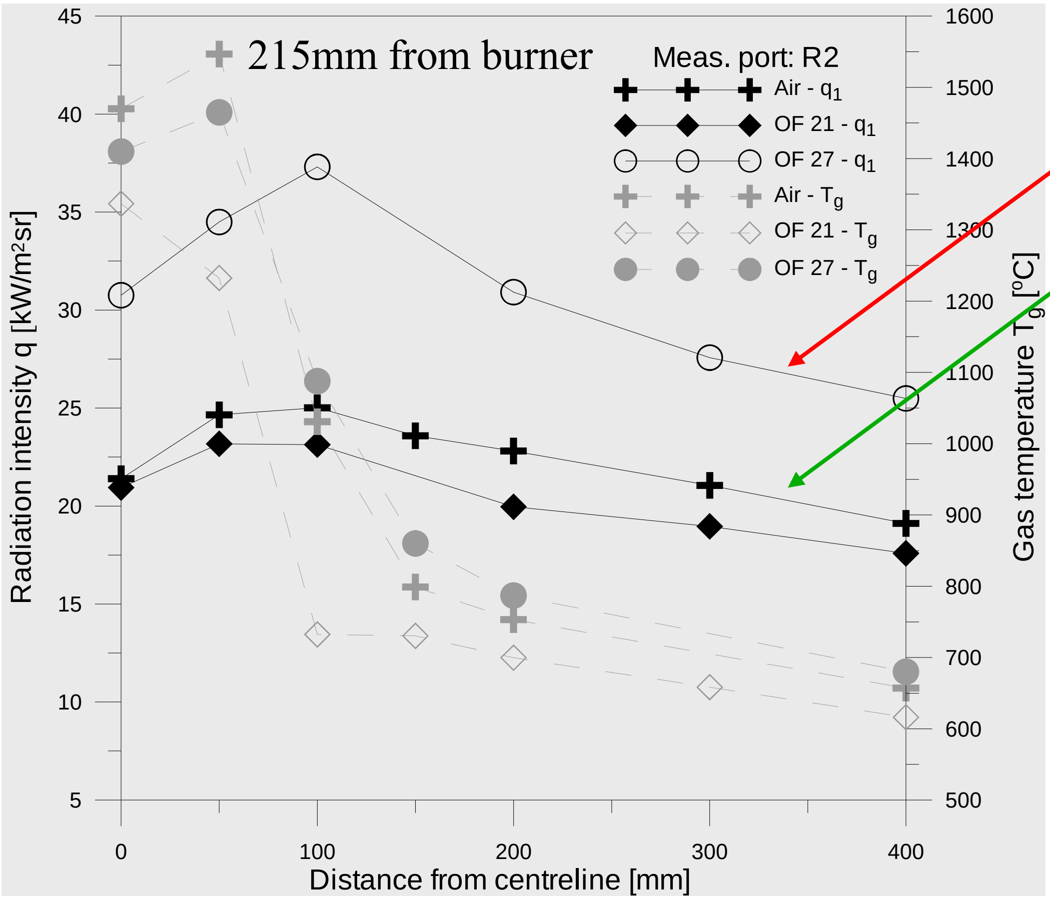


- Profile: centreline to furnace wall
- Reaction zone
- Oxyfuel combustion: temperature control by flue gas recycle rate:

● OF27

❑OF 21

Radial temperature and radiance profiles



- OF 27 case similar temperature levels as for air. Radiation intensity from the flame increases 20-30%.
- Change in emissivity
  - Gas radiation
  - Soot radiation

Gas emissivity

Air case: $\varepsilon_g = 0.23$

OF 27 case: $\varepsilon_g = 0.29$

Mean Radiation Temperature

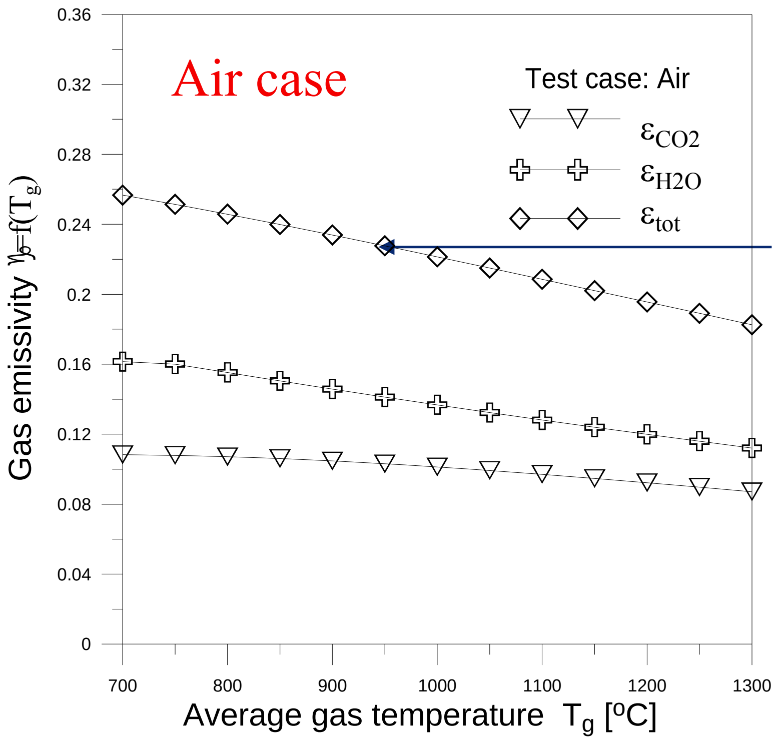
$T_{mr} = 930^{o}C$

$T_{mr} = 950^{o}C$

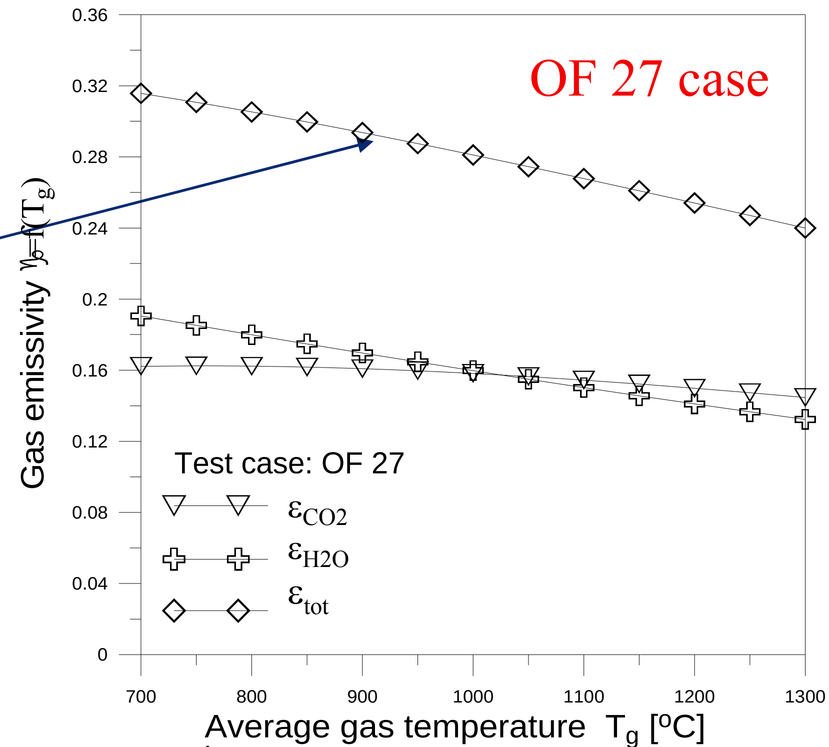
Mean emissivity

Air case: $\varepsilon_m = 0.40$

OF 27 case: $\varepsilon_m = 0.52$



ε_{tot}



Test case	p_{CO2}	p_{H2O}	T_s [K]	L [m]
Air	0.10	0.14	928	0.80
OF 27	0.78	0.18	953	0.80

Summing up

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 O_2-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 performance/burn-out behavior
- The radiation intensity of the OF 27 flame increases with about 20-30% despite similar temperature profiles as in air case
- Increased emissivity in the OF 27 case is both due to increased gas band radiation as well as an increased soot volume fraction

CHALMERS

RESULTS FROM LIGNITE-FIRED TESTS

Test conditions Chalmers 100 kW test unit

Total operation time on lignite: ~1000 h

- With oxy-fuel conditions: ~300 h
- Total measurement time: ~220 h

Same overall stoichiometry for all test cases: λ = 1.17

Oxy-fuel test conditions:

OF 27: (27% global O_2 fraction in feed gas)

- OF 27 for coal compares rather well to OF 27 for gas.
  - combustion temperatures and flame stability are similar
  - Slightly higher flame temperatures than for air

OF 25 and OF 29

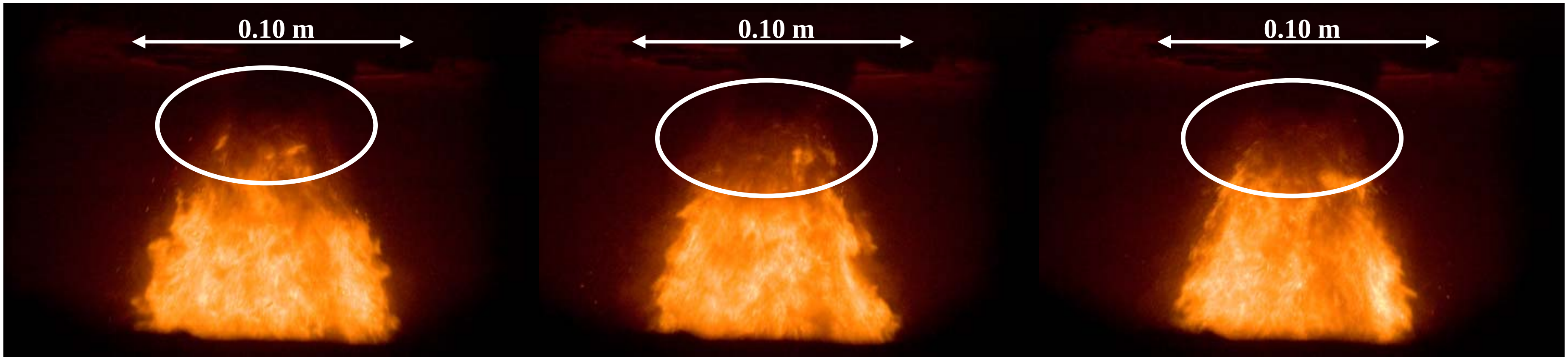
- Temperatures around ash melting point achieved already for OF 29 (around 1350 C)
- OF 25 results in rather similar temperatures in the flame zone

Measurements performed at Chalmers

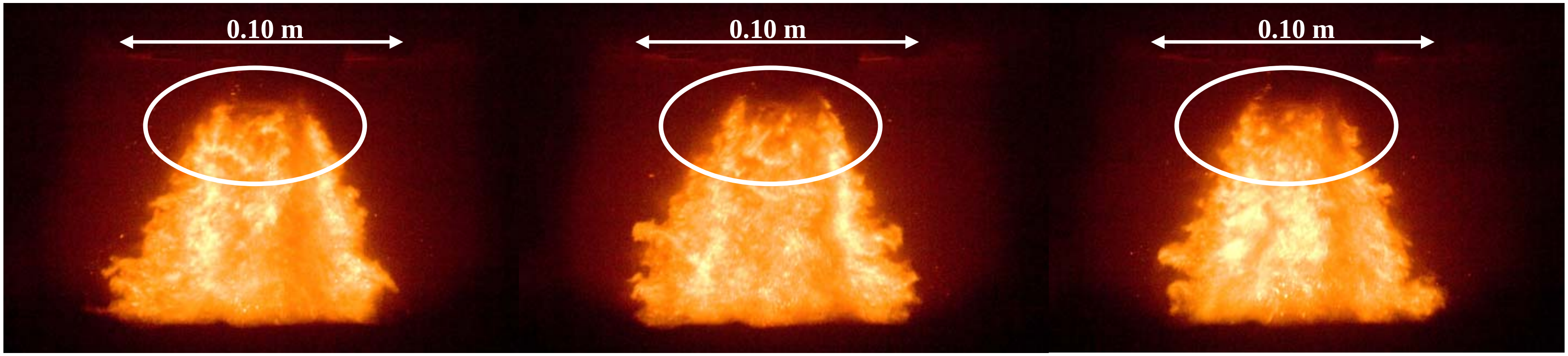
- Gas concentration profiles
  - O_2, CO, HC, CO_2, NO_x, SO_x
  - suction probe/online gas analysis
  - SO_3 measurements
- Temperature profiles
  - suction pyrometer (thermocouple type B, 2000K)
- Radiation Intensity profiles
  - Narrow angle radiometer (IFRF type)
- Particle mass concentration profiles
  - Isokinetic sampling probe
- Burn-out profiles (isokin. samp.)

Flame emission from lignite-fired flames in air and OF 27 environments - Pictures taken @ burner inlet

Air-fired flame: λ = 1.17 (O_2 excess in flue gas: 3.0 vol%)

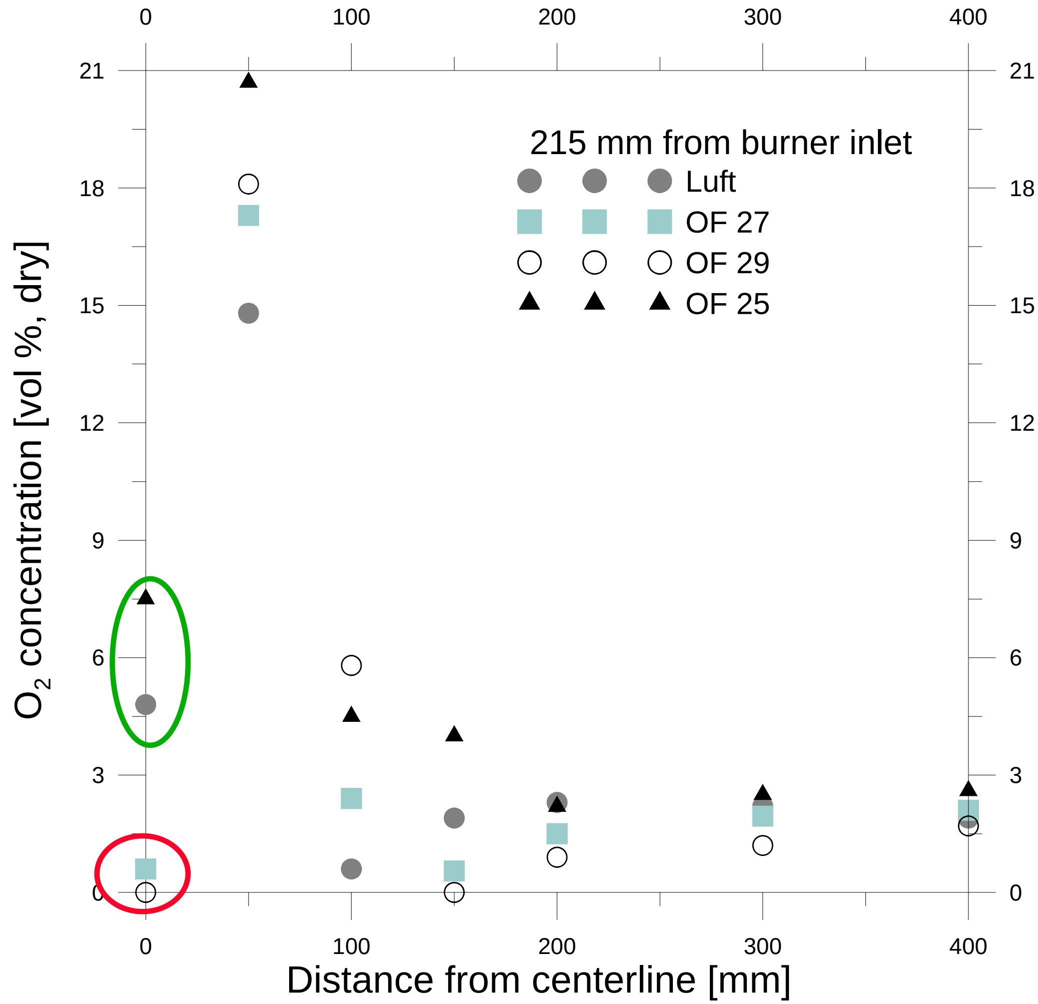


OF 27: λ = 1.17 (O_2 excess in flue gas: 4.0 vol%)



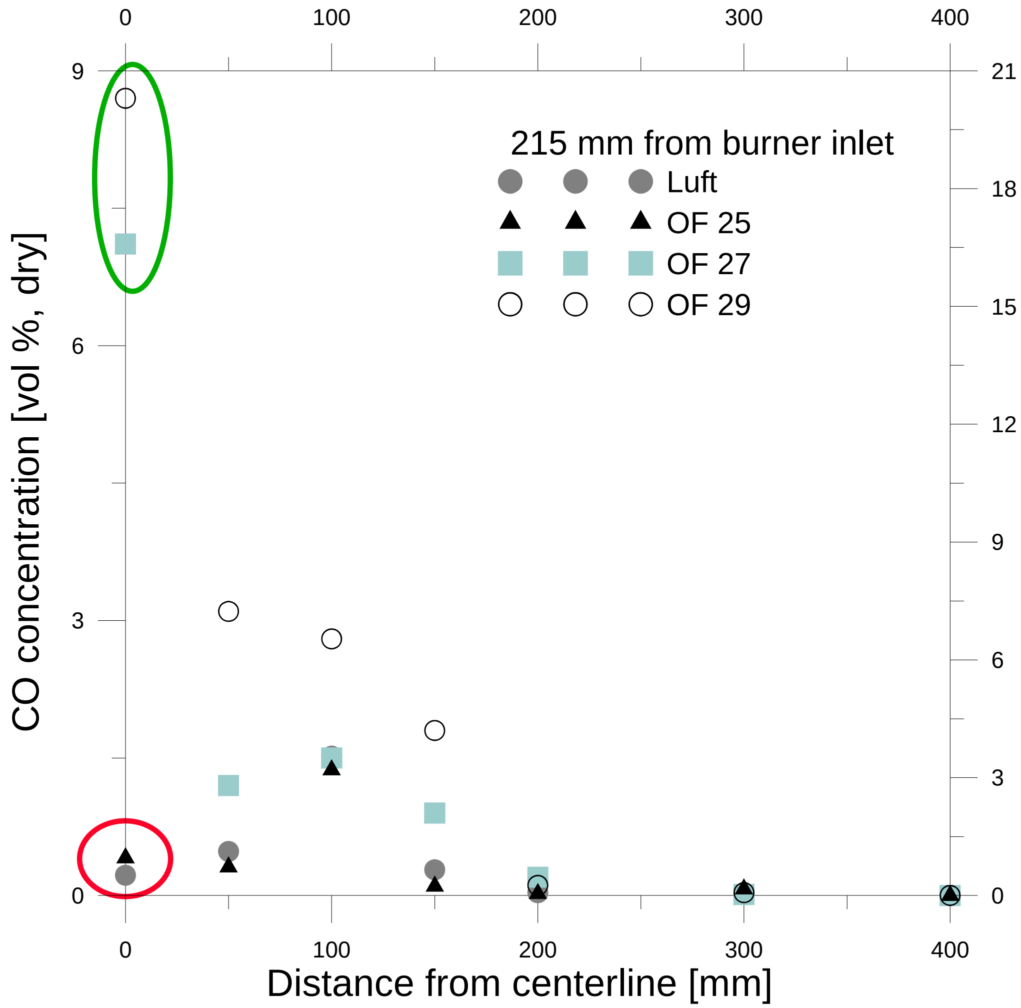
O_2 profiles, 215 mm from burner inlet

- Difference in ignition can be detected from O_2-profile measurements
- Oxygen consumed faster in OF 27 and OF 29 flames compared to OF 25 and air-fired conditions.



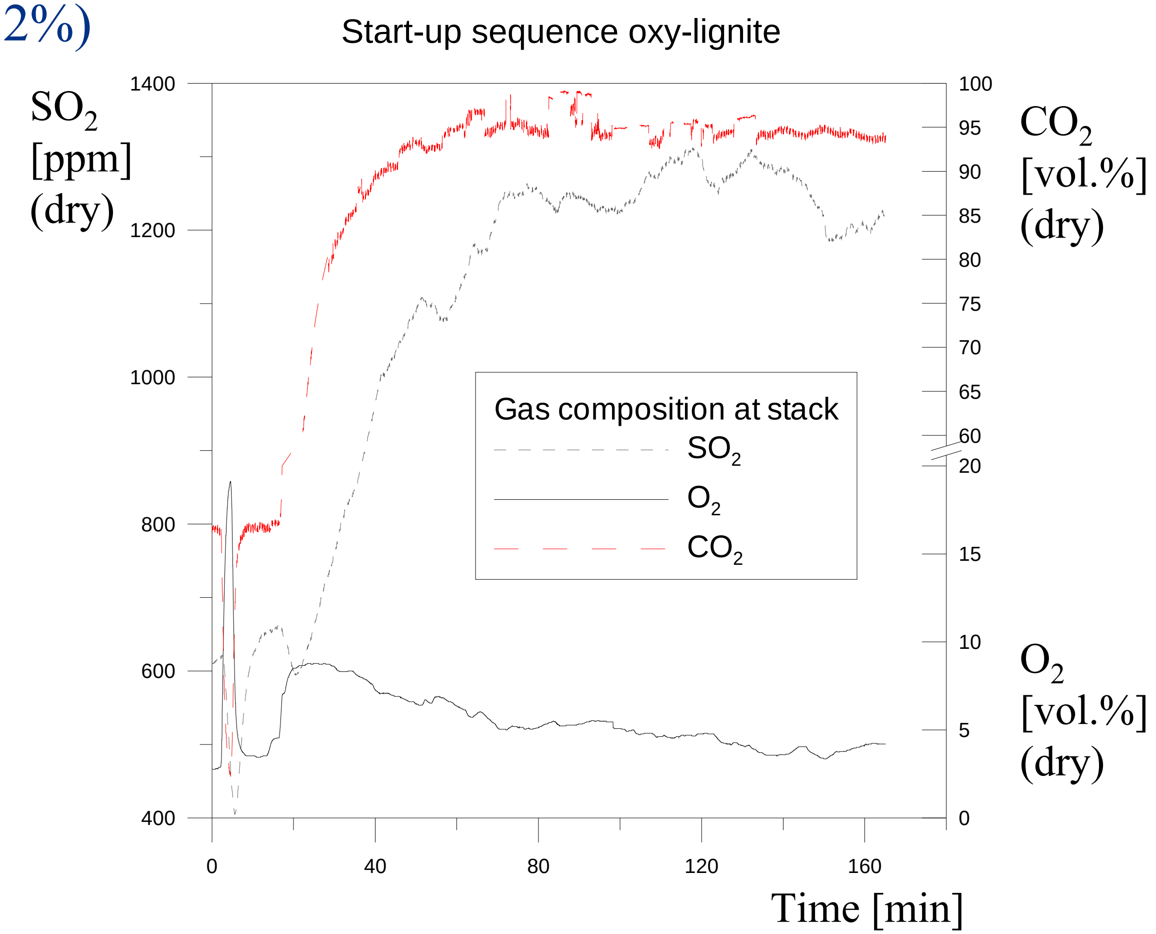
CO profiles, 215 mm from burner inlet

- And marked differences in ignition can also be detected from the CO-profiles
- High centreline CO concentrations for OF 27/OF 29
- Little CO formation in air/OF 25 flames on centreline



Start-up sequence from air to OF 27 conditions

- O_2, CO_2, SO_2 before condenser
- Total concentration level about 98-98.5%, i.e. very low leakage levels (below 0.2%)
- Stable $CO_2/SO_2/O_2$ Levels after 120-160 min
- Feed gas composition as measured:
  26.9 vol% O_2
  71.6 vol% CO_2
  (Discrepancy from 100% mostly due the Argon in the Oxygen feed)



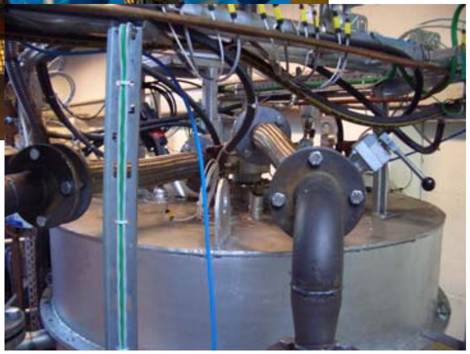
Emission concentrations measured at combustor outlet

->Small differences in CO emissions between air and oxy-cases

->SO_2 and NO_x accumulated in the recycle loop, but emission rates [mg/MJ] significantly lower than for air

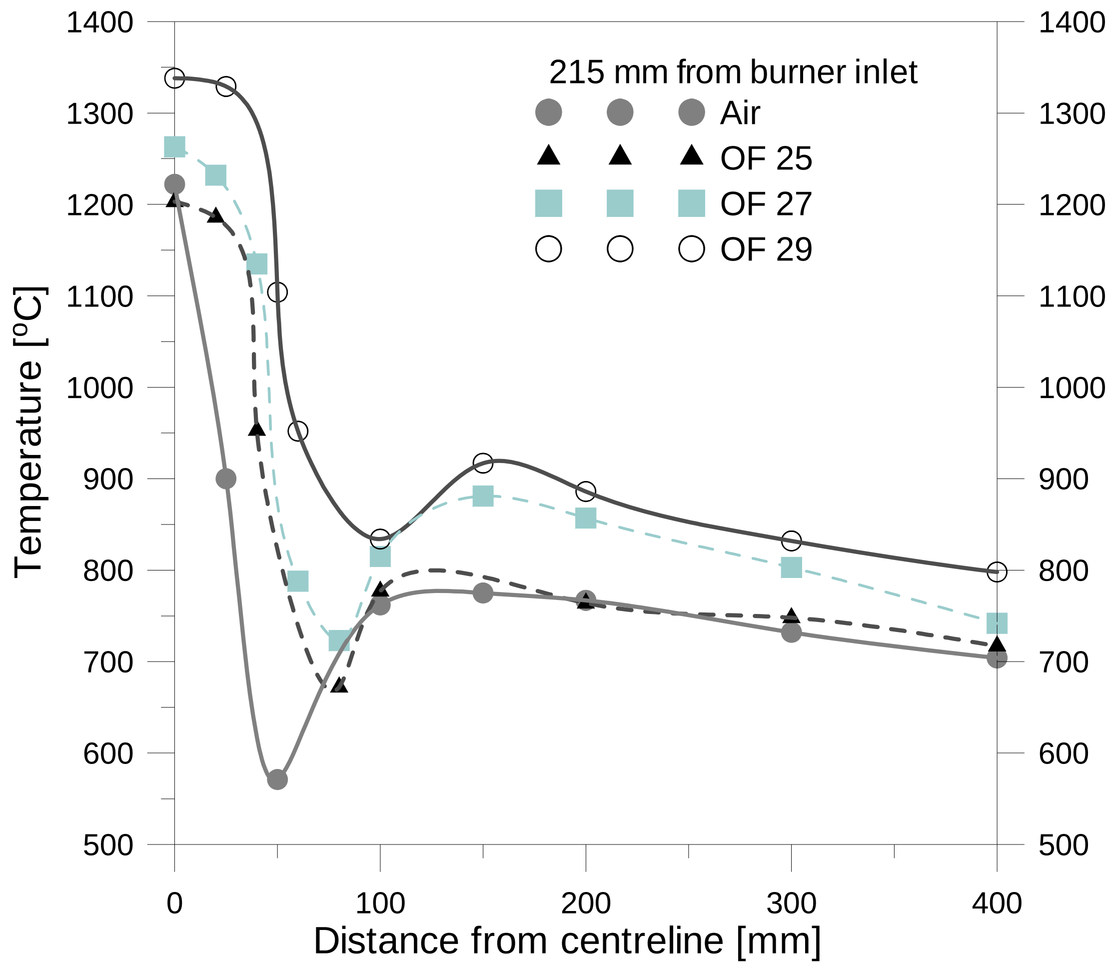
-> SO_2 level reduced to about 40%
-> NO_x level reduced to less than 30 %

	CO [ppm]	NO_x [mg/MJ]	SO_2 [mg/MJ]
Air	130	233	510
OF 25	210	56	181
OF 27	170	62	187
OF 29	150	65	199



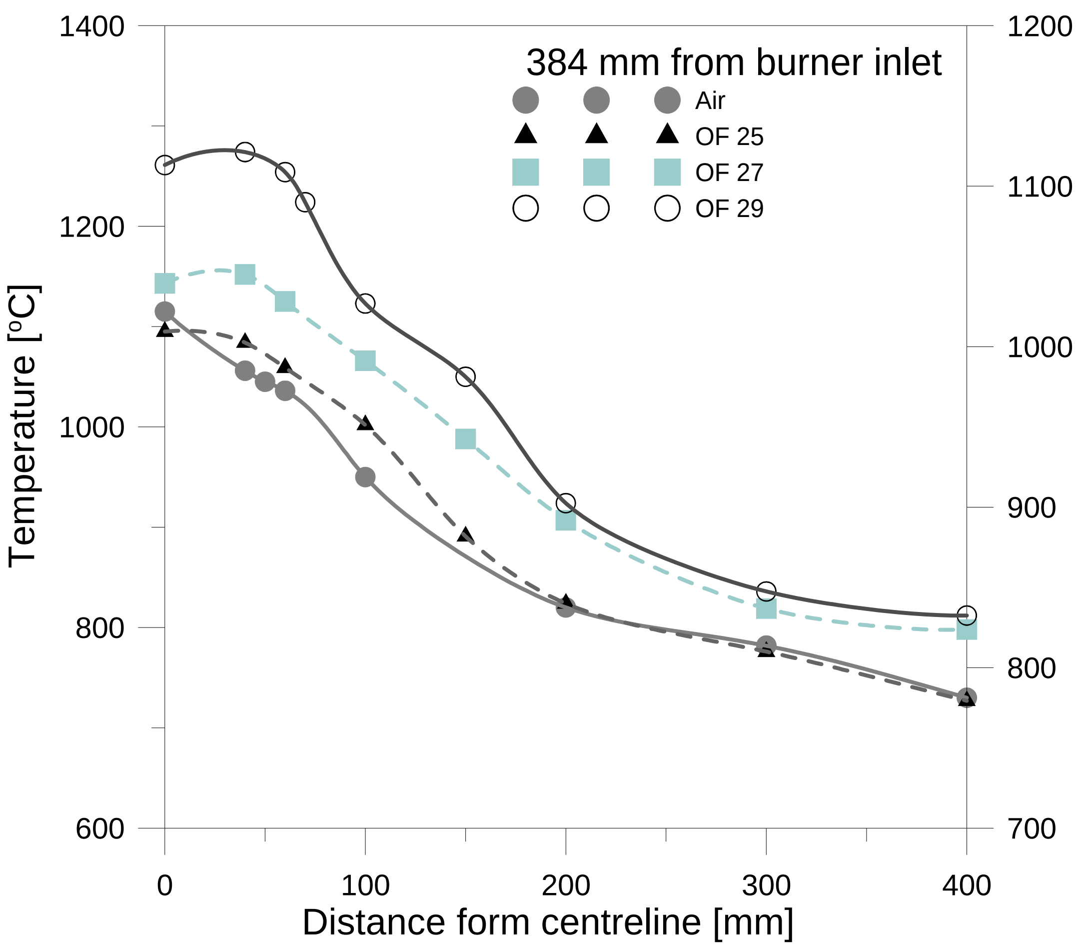
Temperature measurements 215 mm from burner inlet

- Oxy-fuel temperatures increase smoothly with decreasing recycle rate with highest temps for OF 29
- Inlet velocities increase with higher recycle rate
- Impulse from primary stream stronger for Air and OF 25 compared to OF 29



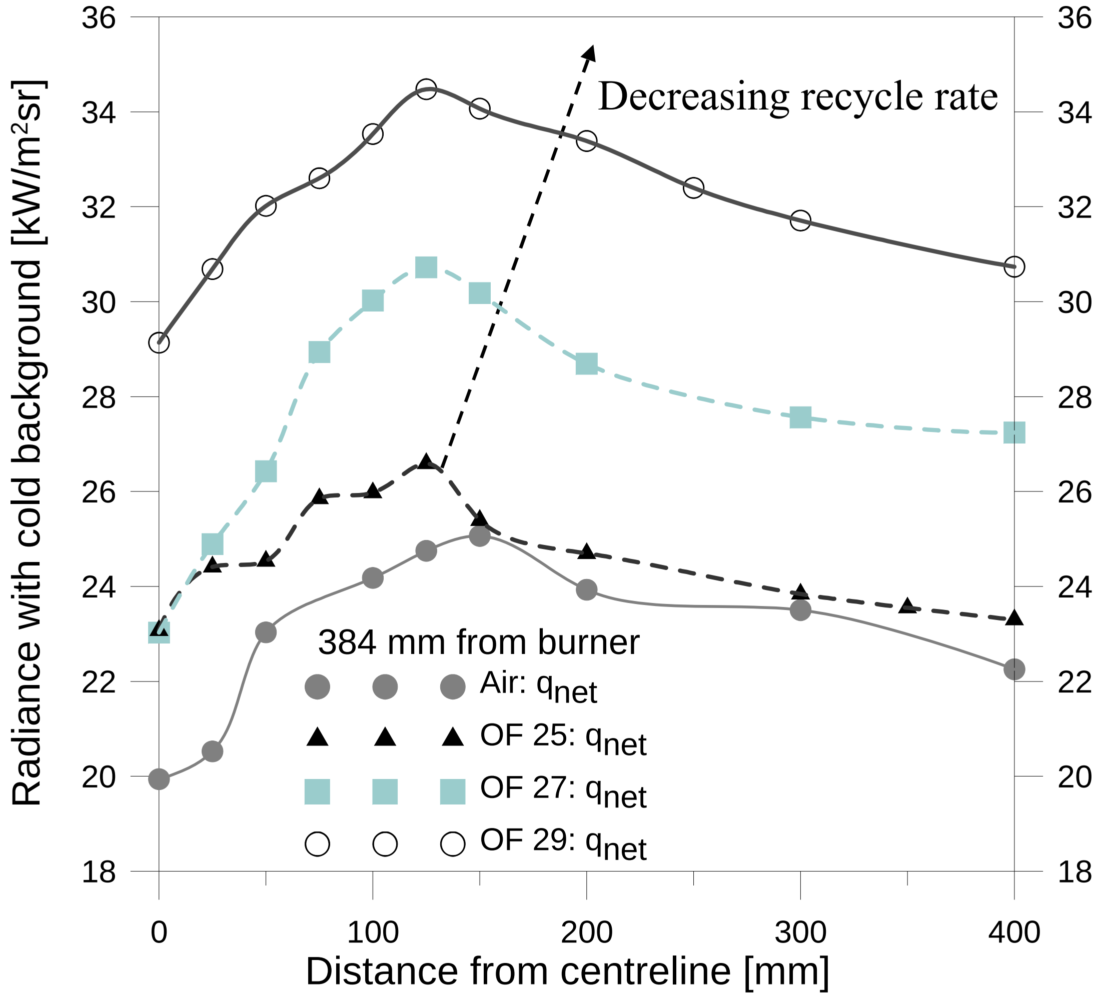
Temperature measurements 384 mm from burner inlet

- Temperatures for Air and OF 25 similar at most flame positions



Radiance measurements 384 mm from burner inlet

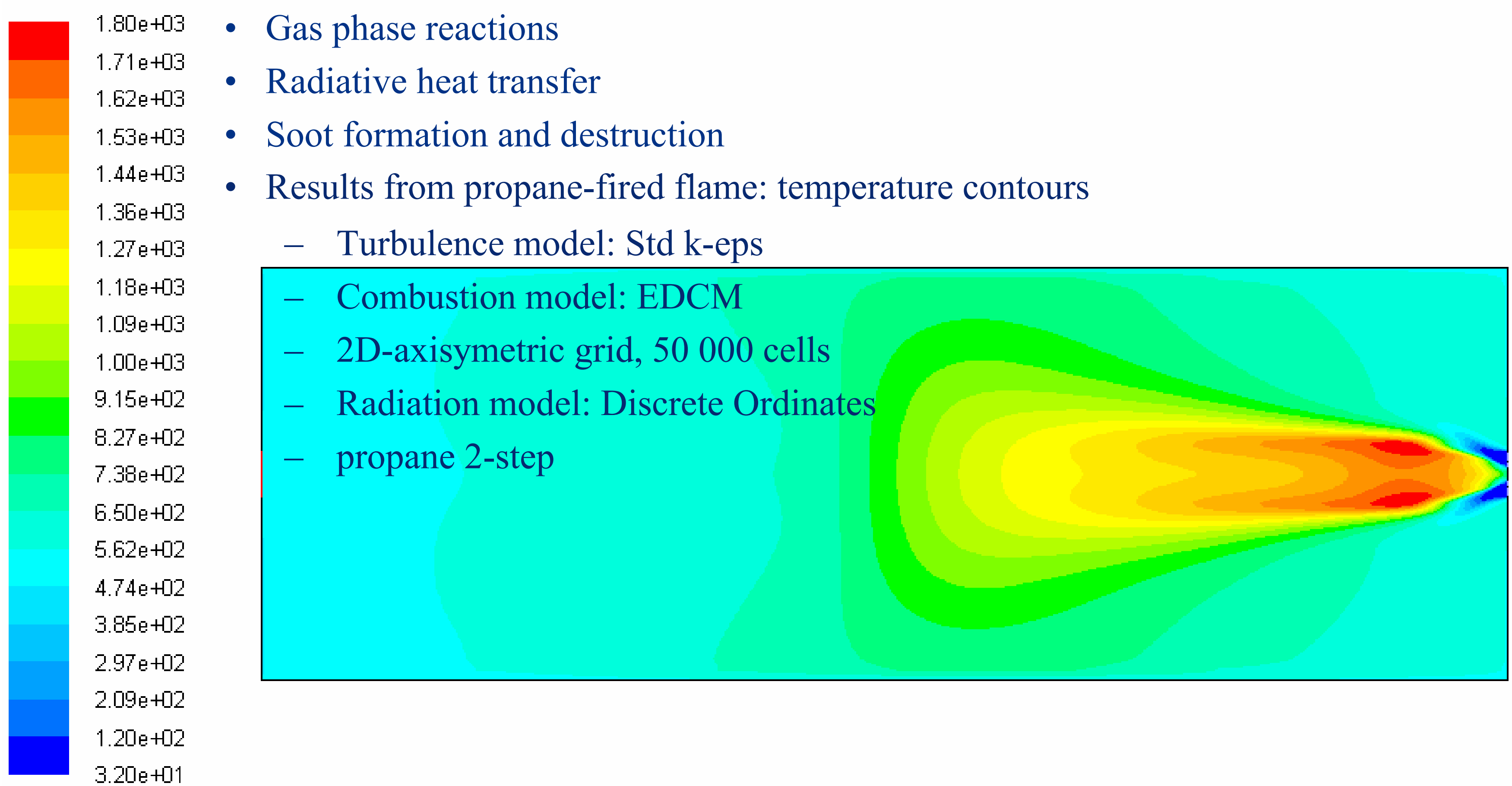
- Radiation intensities similar for Air and OF 25 – in analogue with the measured temperatures.
- Radiation increases with decreasing recycle rate.
- Particle radiation dominates the radiation in both air-fired and oxy-fired environments.



CFD-modeling of the 100 kW combustor

Important tool in the scaling from semi-industrial to pilot to demo

- Evaluation of the various sub-models (here FLUENT) for
  - Gas phase reactions
  - Radiative heat transfer
  - Soot formation and destruction
  - Results from propane-fired flame: temperature contours
    - Turbulence model: Std k-eps
    - Combustion model: EDCM
    - 2D-axisymetric grid, 50 000 cells
    - Radiation model: Discrete Ordinates
    - propane 2-step



Radiation modeling

- Using the radiation data from the gas-fired flame
  - Down stream of flame with near pure gas radiation: EWBM and WSGGM models tested against data
  - Choose gas radiation model
  - In-flame positions modeled to obtain soot volume fractions/absorption coefficients
  - Evaluate performance of radiation & soot formation models in CFD tool (FLUENT)
- Using the radiation data from the coal-fired fame
  - Add particle radiation model to evaluate the lignite-fired data
  - Model will be a valuable tool in the evaluation of the radiance measurements in the Schwarze Pumpe Pilot
- The ultimate aim is that the CFD modeling work can be scrutinized and that the CFD model approach can be improved and/or made more efficient

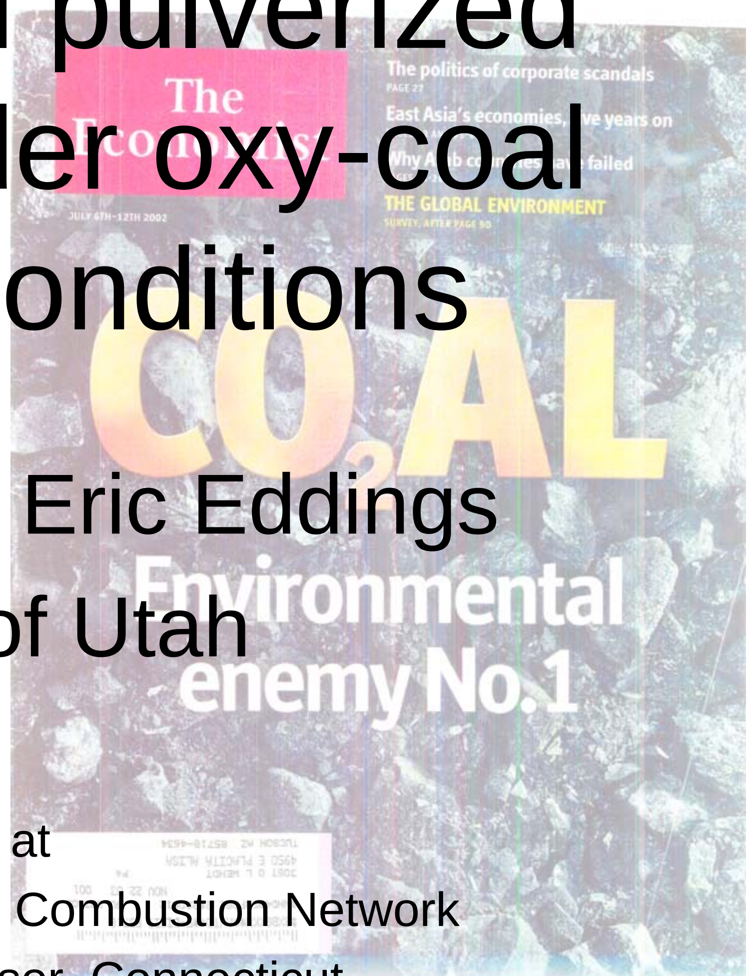
Nitrogen and Sulphur chemistry

- Nitrogen chemistry
  - Fuel-N formation and recycled NO destruction need further clarification
  - Special designed experiments have been carried out for N-chemistry modeling purposes
  - Sensitivity of NO formation to air ingress and stoichiometry has e.g. been tested
- Sulphur chemistry
  - As for the Nitrogen chemistry, the ultimate goal is to develop a model of the Sulphur chemistry which works satisfactory for oxy-conditions
  - The mass balance need to be closed
  - SO_3 formation need to be determined for various oxy-conditions
  - Ash retention is an other important source for differences between oxy and air-fired conditions

Industrial scale oxy-fuel combustion - outlook for pilot testing

- Scale up of experiments – 30 MW_{th} pilot plant
  - From mid 2008: Participation in the Vattenfall pilot plant testing
  - Combustion research carried out by IVD, Chalmers and the other industrial partners involved
  - Use gained knowledge from 20/100/500 kW_{th} units
    - Establishment of test conditions of interest
    - Expected overall combustion behaviour
    - Combustion modeling tools
  - Revisit smaller scale tests from issues arising in 30 MW pilot

Stability of axial pulverized coal flames under oxy-coal combustion conditions



Jost O.L.Wendt & Eric Eddings
University of Utah

Presented at
2nd Workshop of the Oxy-Fuel Combustion Network
Hilton Garden Inn, Windsor, Connecticut
January 25 -26, 2007

Acknowledgements

To those that have actually done the work.

- University of Arizona
  - Gregory Ogden,Ph.D.,
- University of Utah
  - Jing-Wei (Simon) Zhang, Ryan Okerlund
- Funding
  - US Department of Energy, University of Utah Clean Coal Center (UC^3, Co-Directors Ron Pugmire and Adel Sarofim)
  - US Department of Energy University Coal Research Program (to U. Arizona)

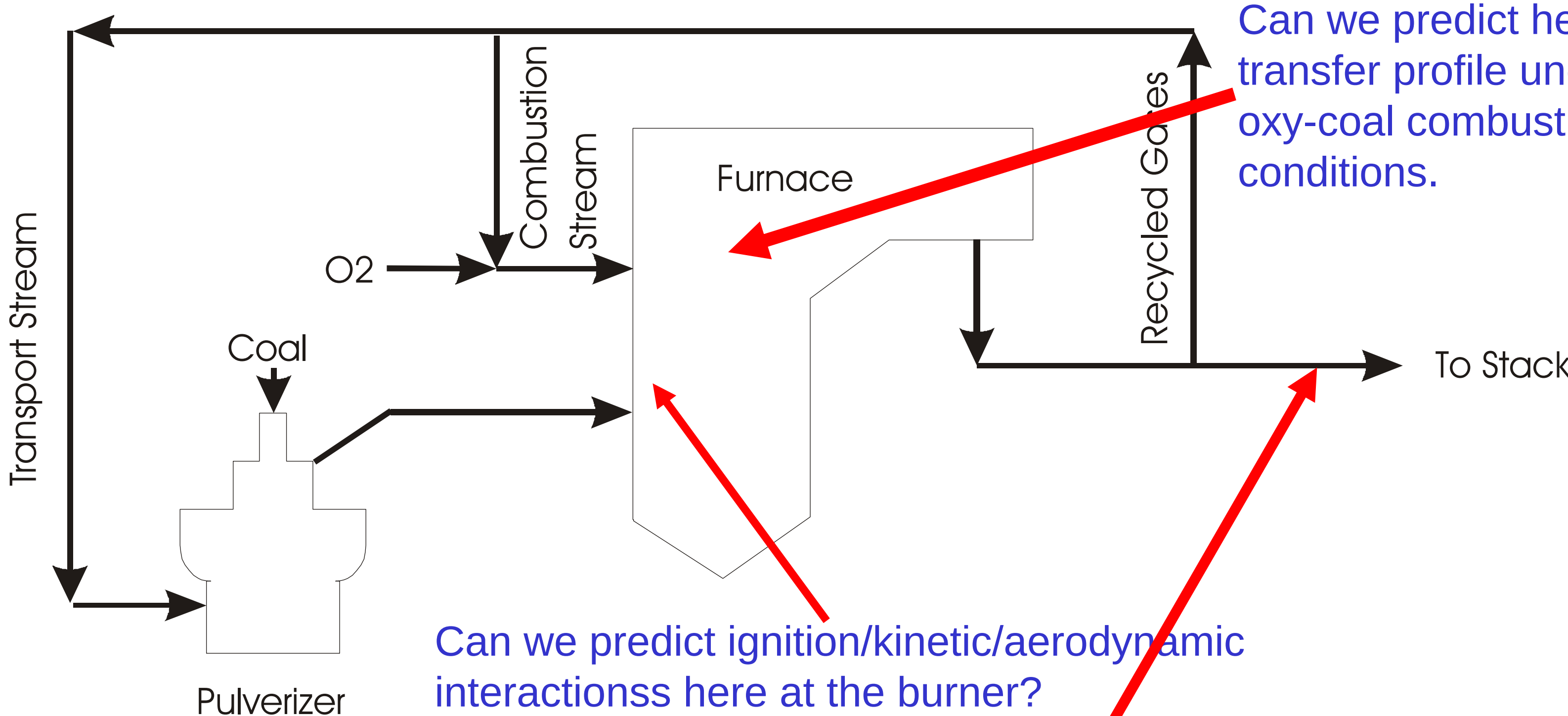
THE UNIVERSITY OF UTAH

Scope of this presentation.

1. Sample of current oxy-coal combustion research at the University of Utah
   - Work in progress
   - Based on:
2. Previous completed research at University of Arizona
   - Oxygen enrichment
   - Coal fines

Oxy-Combustion:

Schematic of oxygen fired PC furnace with CO_2 recycle (*Sarofim et al, 2004*)



Can we predict heat transfer profile under oxy-coal combustion conditions.

Can we predict ignition/kinetic/aerodynamic interactionss here at the burner?

How much residual N_2, NO, Hg, SO_2, trace metals etc. can be removed with the CO_2 to be sequestered?

THE UNIVERSITY OF UTAH

Oxy-fuel combustion issues

- Recycle gas volume
- Where to withdraw recycle gas
- Heat transfer
- Flame stability
- Ignition
- NO_x, SO_x, Hg, trace metals
- Model validation (coal, aerodynamics, heat transfer etc.)

THE UNIVERSITY OF UTAH

Oxy-Coal Combustion Research at U of U:
Vision for this project

- Build experimental facility to address *technical issues* related to oxy-coal combustion with carbon sequestration.
- Focus on *understanding* (high temperature) *processes* involved rather than inventing devices (burners).
- Develop *enabling technology* to allow commercialization of oxy-coal combustion within the near term.
  - Existing units?
  - Build on current technology?
  - "Baby step" approach?

THE UNIVERSITY OF UTAH

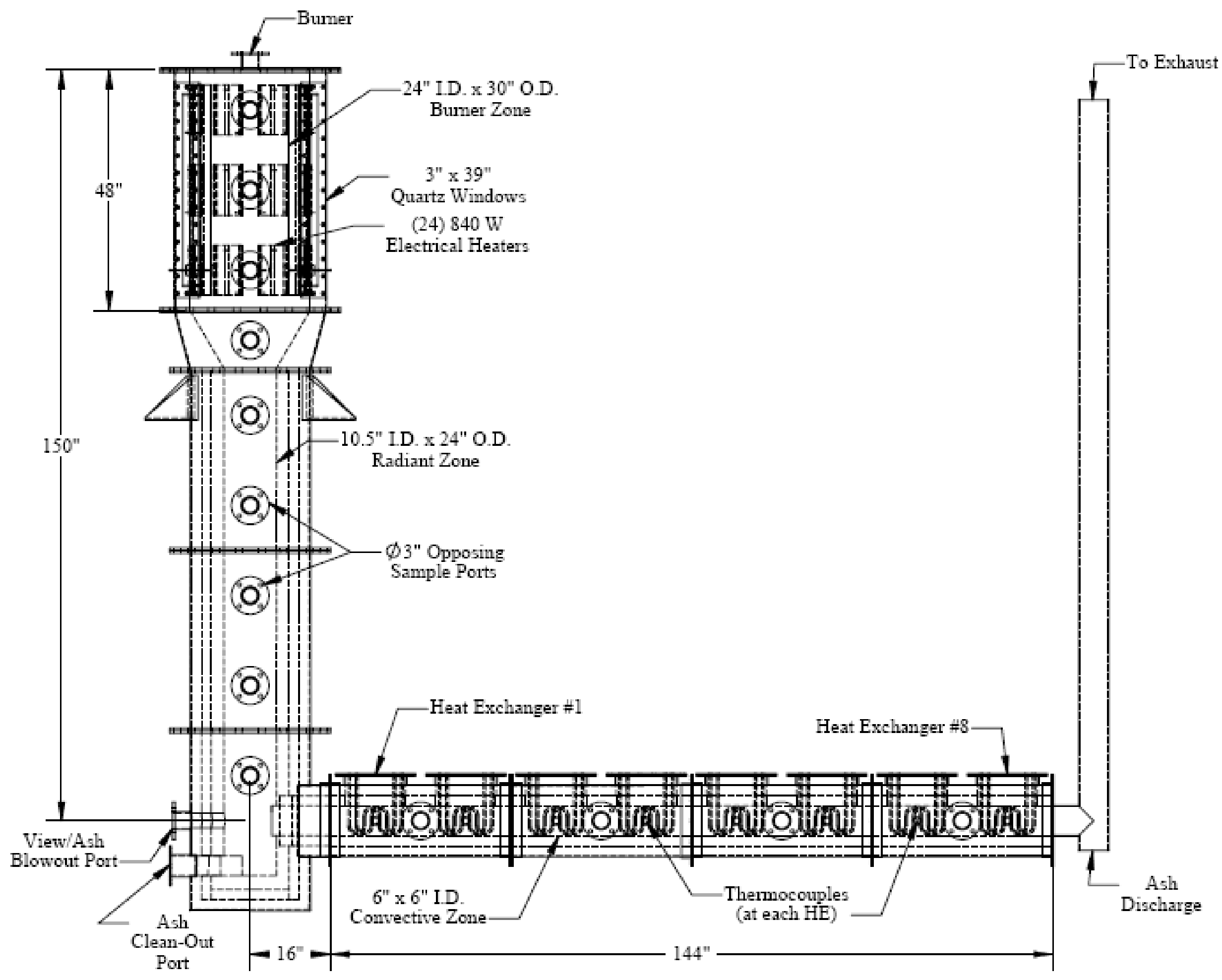
Oxy-Coal Combustion Research at U of U: **Vision contd.**

- Focus on *simulation validation* (for retrofit).
- *Well defined*, axial Type 0, pulverized coal diffusion flames (*no* swirl)
- Simulates large class of practically relevant near flame aerodynamics
  - Cement kilns
  - Tangentially fired boilers.
- *Systematic* control of axial burner variables
  - Momenta, flows, velocities (using sleeves)
  - Composition, P_{02} , P_{C02} in
    - Transport fluid
    - Secondary oxidant
  - Wall temperature

THE UNIVERSITY OF UTAH

Task Oxy 1.1 - Progress

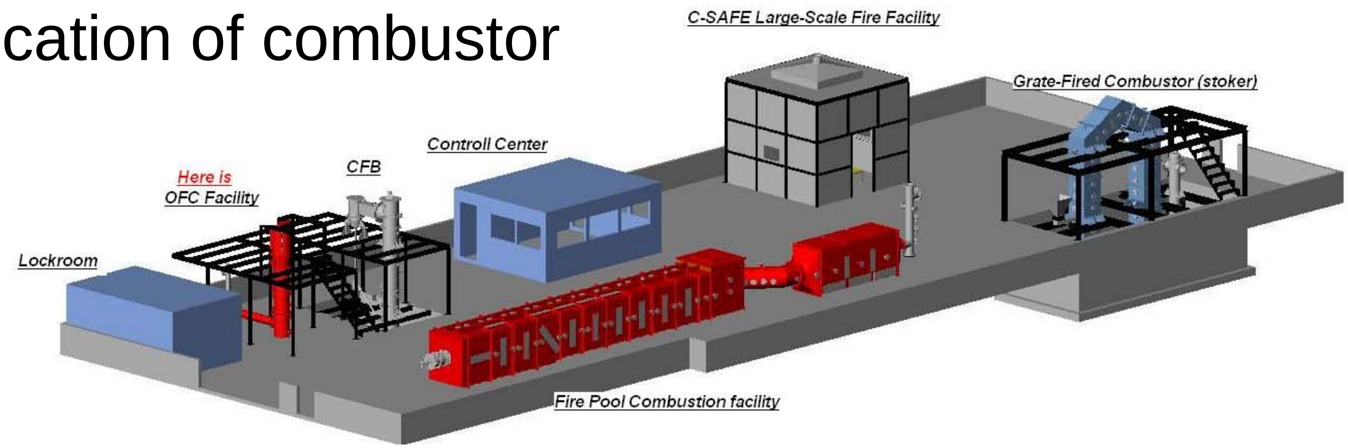
Design, construct, and troubleshoot a new down-fired 100kW, oxy-coal combustion furnace.



THE UNIVERSITY OF UTAH

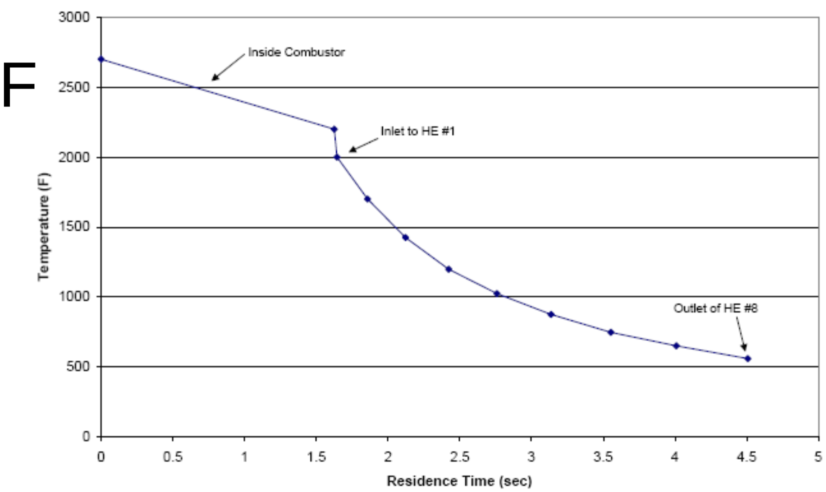
Task Oxy 1-1: Design attributes

Location of combustor



Design temperature profile

T, ^{0}F



τ, sec

THE UNIVERSITY OF UTAH

Task Oxy-1: Completed (1st quarter)

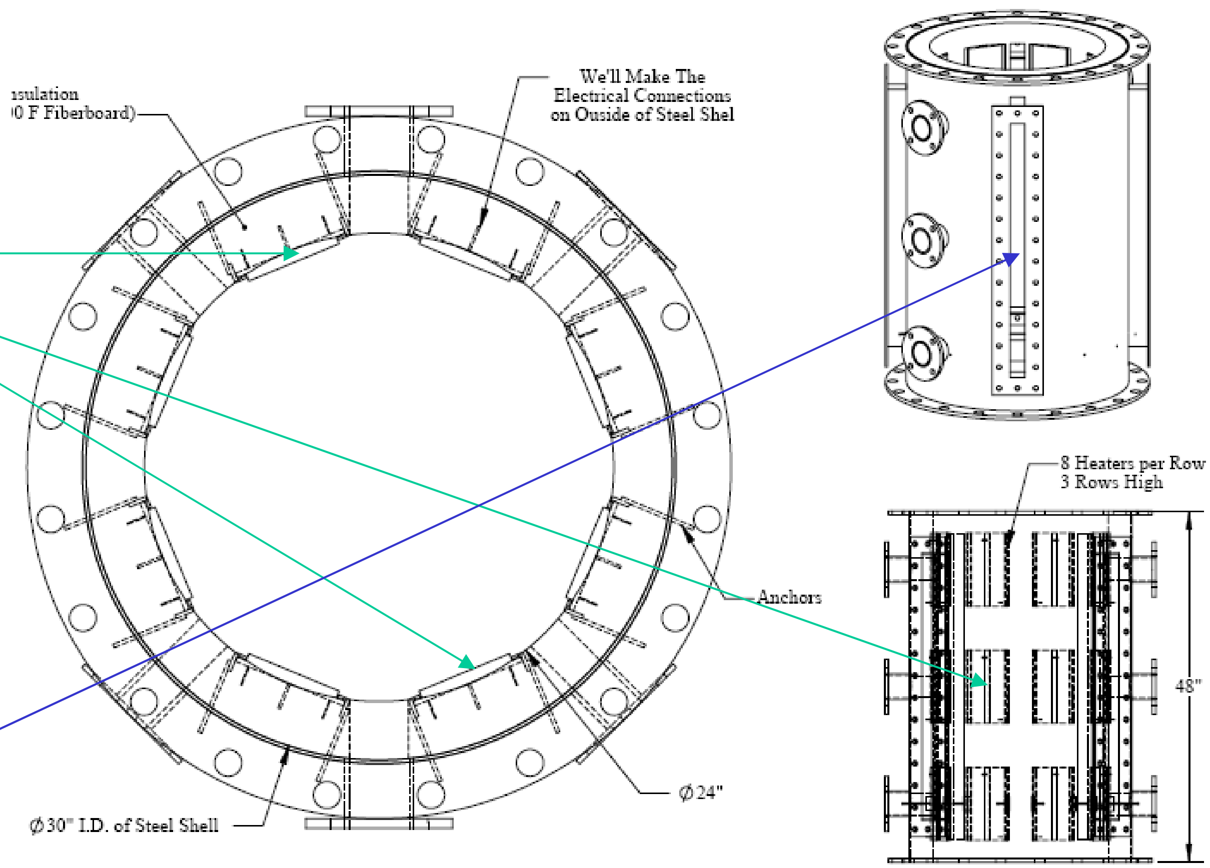
1. Overall design of oxy-fuel combustor
2. Fabrication of structure containing combustor
3. Fabrication
   - Steel shell, with refractory lining
   - Control panel
4. Design of
   - Burner (axial, controlled momentum burner for
     - Air
     - O_2
   - Quartz window for visual observation

THE UNIVERSITY OF UTAH

Task Oxy-1: Completed 1st quarter (continued)

Design and placement of electric wall heaters (24 840W flanged ceramic plate heaters - 3 rows and 8 heaters per row)

Design of quartz window for visual observation and (later) optical diagnostics



THE UNIVERSITY OF UTAH

Current status

Overview

View of inside of upper chamber, showing electric heaters and view windows.

Still to be completed

Task Oxy 1-1

- Complete fabrication of combustor
- Light of with pulverized coal and air
- Complete O_2 delivery train

Task Oxy 1-2

- Coal jet ignition experiments
  - Minimum P_{O2} in primary jet to allow stable ignition
  - Effect of $P_{O2,}$ & P_{CO2} in primary jet on flame attachment

Task Oxy 1-3

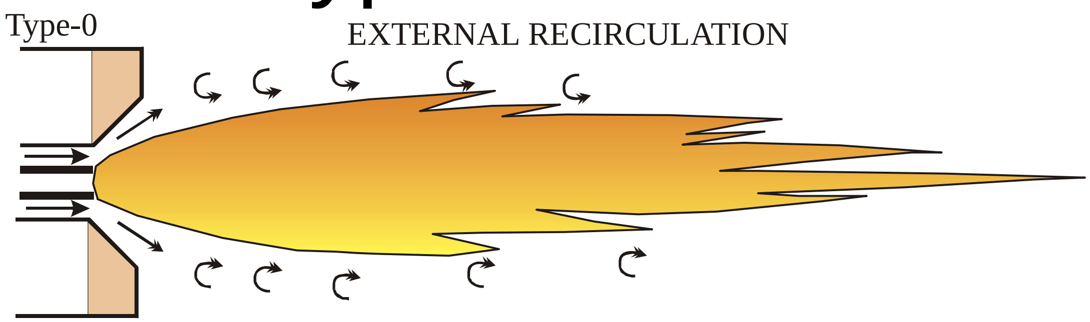
- Preliminary validation of coal jet ignition simulation models

UU work is continuation previous work at University of Arizona

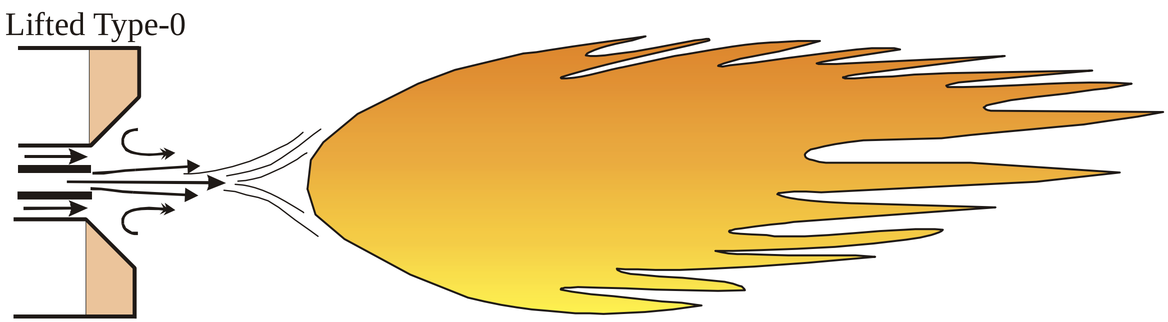
- 17 kW, downfired, heated walls, quartz window
- O_2 enrichment and/or coal fines in primary jet.
- Also restrict to coaxial flames
  - Attachment of Type 0 Flames
    - No secondary air swirl
    - No *internal* recirculation zone
- Represents corner fired boilers and cement kilns
  - *Well defined* aerodynamically
  - Good *prototype* configuration to validate models through systematic variation of *known* parameters.
  - Flame standoff distance has been identified as key parameter for NO_x emissions in cement kilns

THE UNIVERSITY OF UTAH

Type 0 Flames



ATTACHED DIFFUSION FLAME



PARTIALLY PREMIXED FLAME

THE UNIVERSITY OF UTAH

Flame aerodynamic issues and O_2 enrichment: Questions addressed.

(Greg *Ogden, Ph.D dissertation, University of Arizona, 2002)*

- What is the relationship between O_2 enrichment, near-burner aerodynamics and flame detachment and how can that be measured?
- What effect does oxygen partial pressure in the **transport stream** have on flame stability, flame detachment and NO_x?
- How do coal fines affect combustion stability and pollutant emissions?

THE UNIVERSITY OF UTAH

Project Motivation

- Flame attachment is a critical variable for optimum performance of low NO_x burners for pulverized coal combustion
- Need to promote formation of fuel-rich combustion zone
  - Fuel-N devolatilization
  - Reduction to N_2

THE UNIVERSITY OF UTAH

Approach

- Whereas, under well mixed conditions, oxygen enrichment are known to:
  - Increase combustion intensity, flame temperatures
  - Increase both Fuel and Thermal NO_x
- Under diffusion mixed conditions, oxygen enrichment of **only** transport air
  - Should promote coal ignition and flame attachment
  - Reduce premixing
  - Reduce NO_x

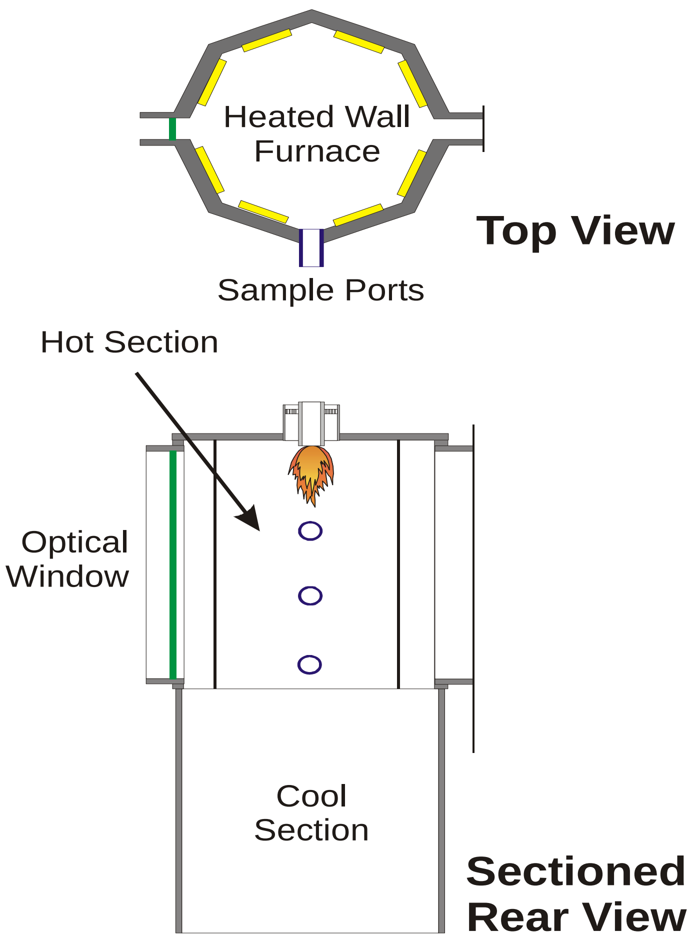
THE UNIVERSITY OF UTAH

Approach-Cont'd

- Restrict to coaxial flames
  - Type 0 Flames
    - no secondary air swirl
    - No internal recirculation zone
- Represents corner fired boilers and cement kilns
  - Well defined aerodynamically
  - Flame standoff distance has been identified as key parameter for NO_x emissions in cement kilns

THE UNIVERSITY OF UTAH

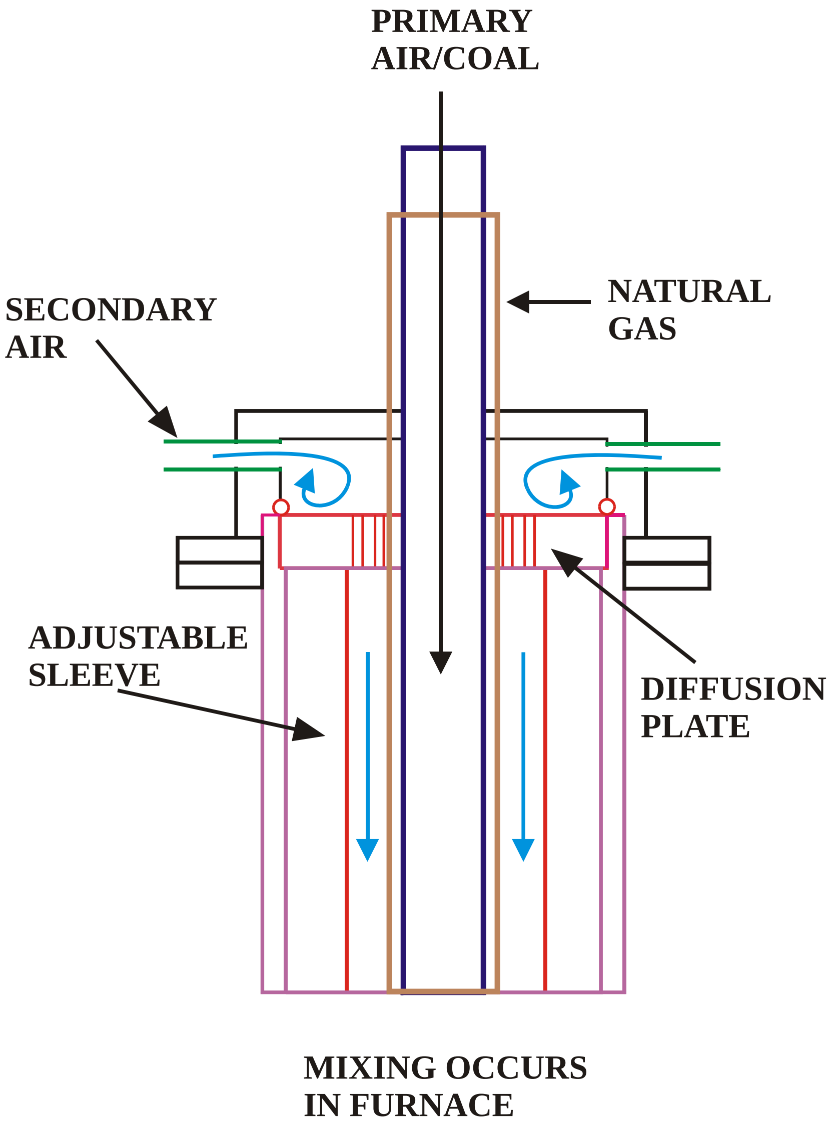
Laboratory Furnace Details



- 18” ID hot wall furnace
  - Designed for “near flame” analysis
  - lightweight refractory
  - Air preheater
- 3’ Hot section
  - Multi-zone ceramic heaters wall temperatures to 1,300 K
  - Full length quartz window for flow visualization studies
  - 4 stationary sampling ports

THE UNIVERSITY OF UTAH

Axial Burner



- Removable sleeves
  - –Velocity is controllable
    - Fuel
    - Combustion air
  - –Maintain constant momentum at different secondary air temperatures
  - –Independently control velocity and momenta
- Supplemental gas injection if reqd.

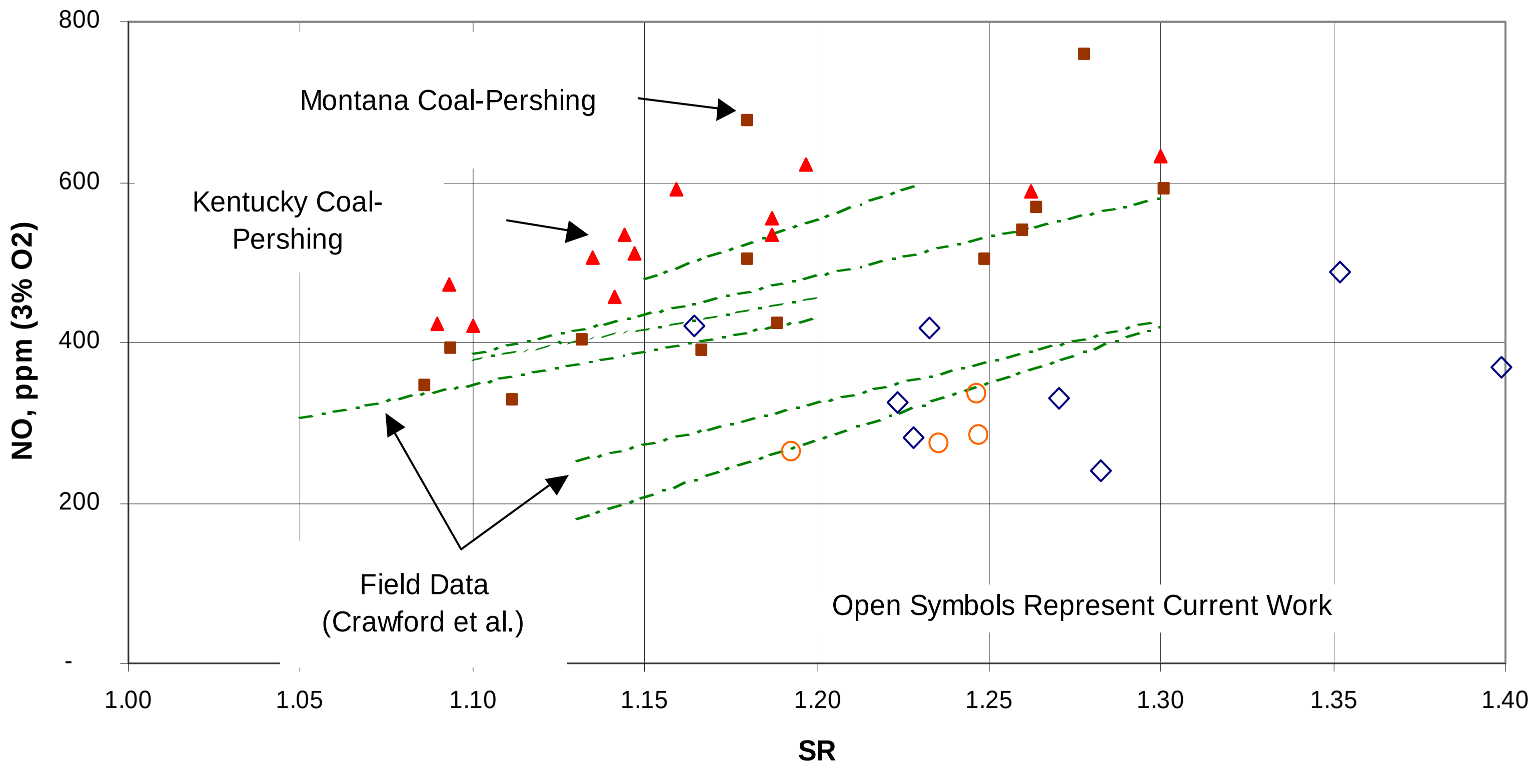
Furnace Layout: UA 17kW furnace

Oxygen Enrichment

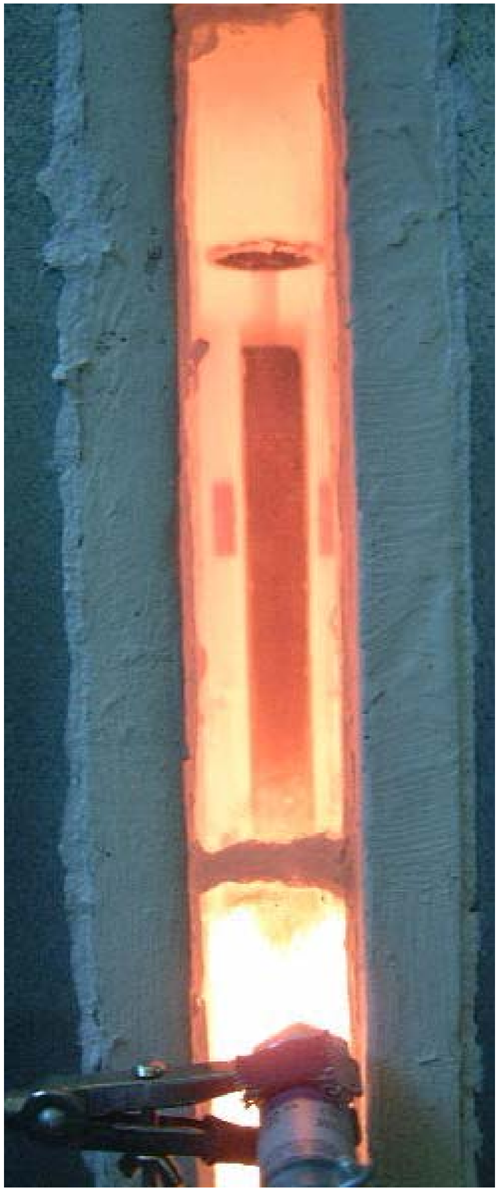
- Varied transport air oxygen partial pressure (Po_2)
  - 20-29% via O_2 enrichment
  - 13% via N_2 dilution
- Furnace wall temperature
  - 750° & 900°C
- General operating conditions
  - 2 kg/hr Utah coal, 1.2 SR overall
  - 450°C air preheat
  - V_c ~31.2 to 32.5 fps

THE UNIVERSITY OF UTAH

Furnace Validation



Attached



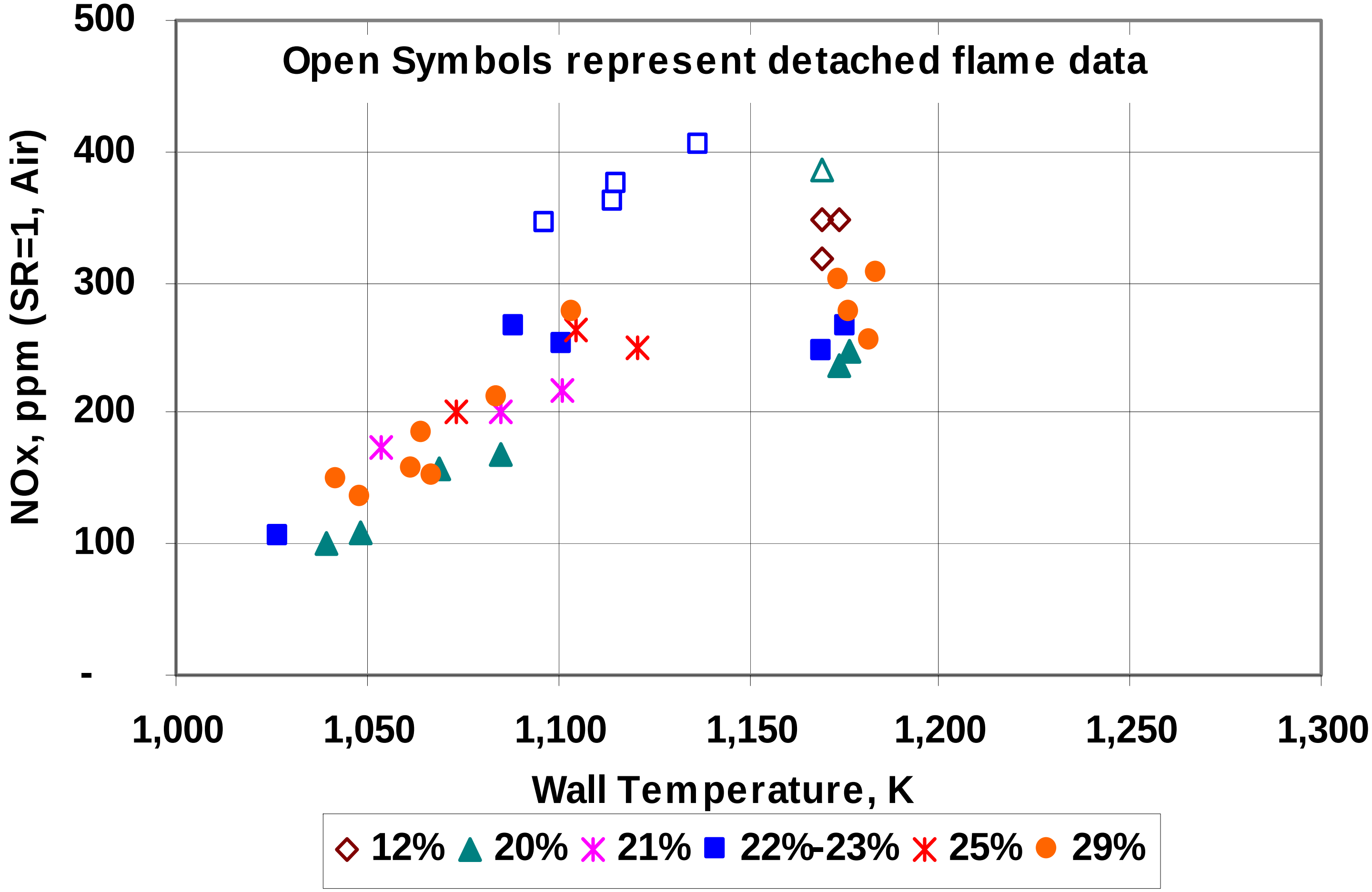
Detached

Coal stream

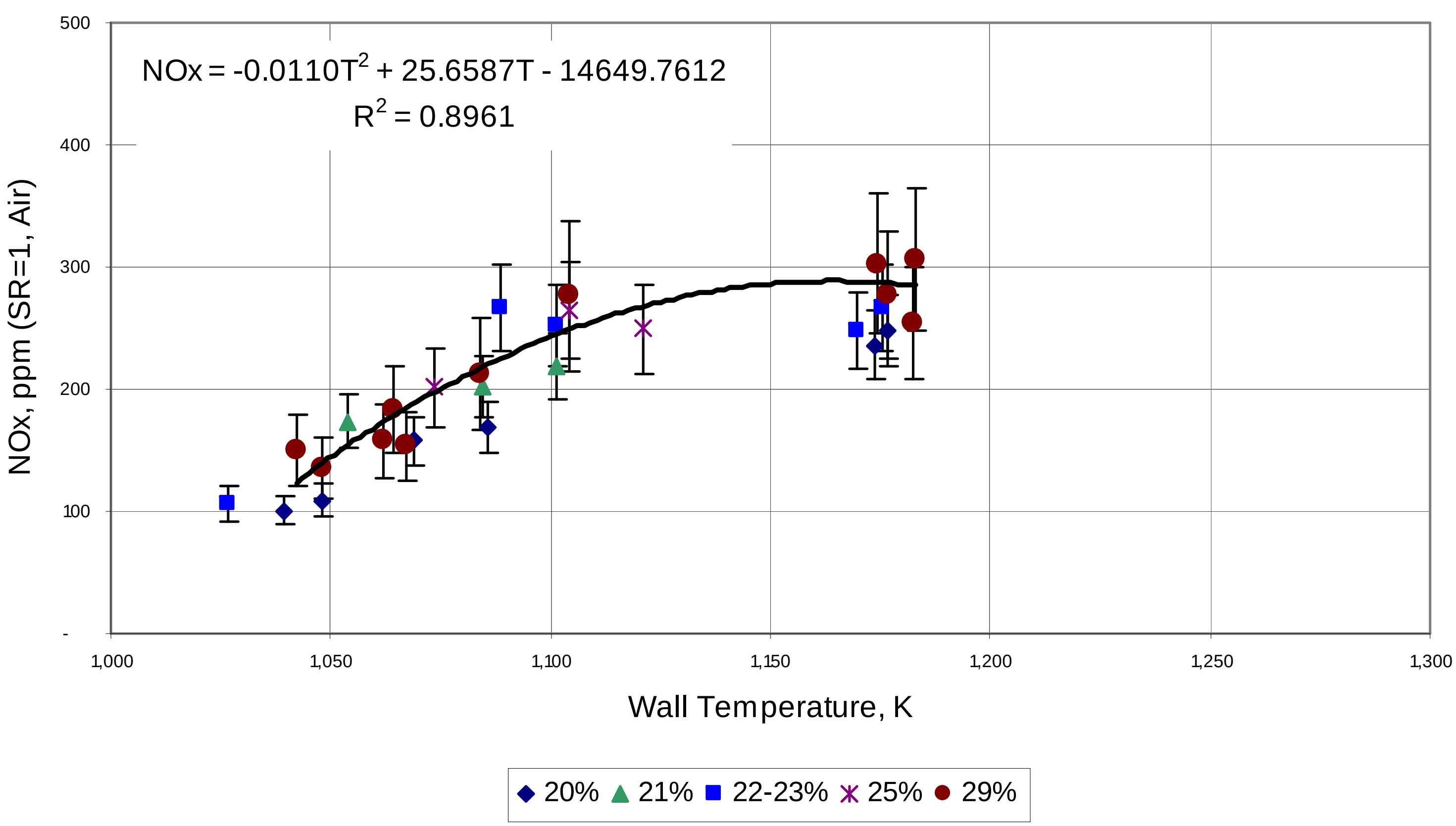
THE UNIVERSITY OF UTAH

Flame Detachment

NO_x Emissions Data



Temperature Effect on NO_x Attached Flames



Subtle P_{O2} Effects

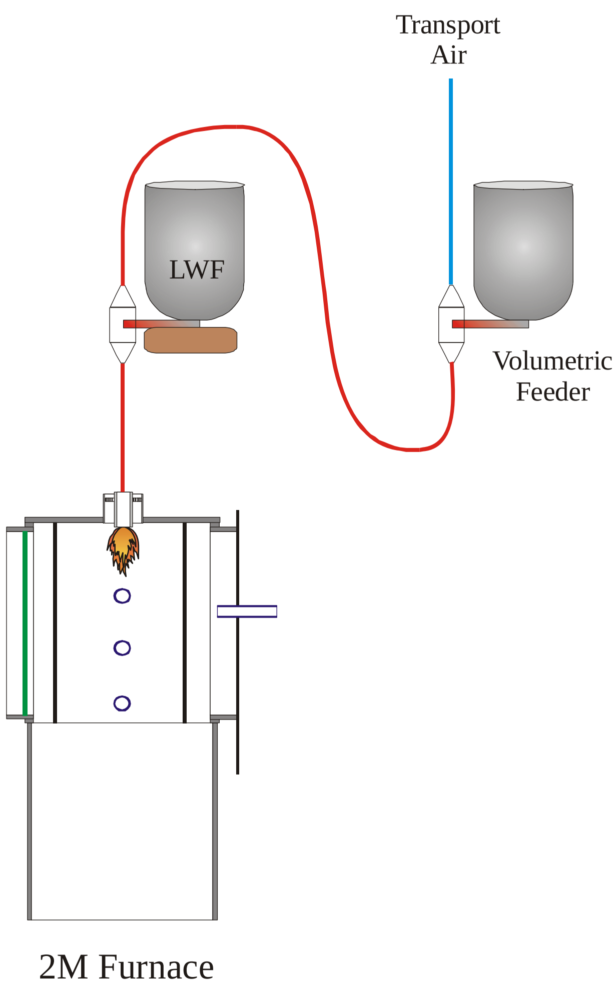
Coal Fines

- Investigate impact of fines fraction for a normal PC distribution
  - Fines-d_p <10 microns
  - 0, 15% (base), 23% and 31% fines
  - 825 & 925°C walls
  - 21 & 29% transport air oxygen

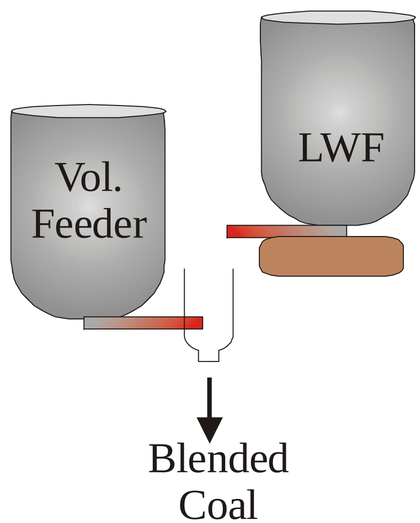
THE UNIVERSITY OF UTAH

Feeding Fines

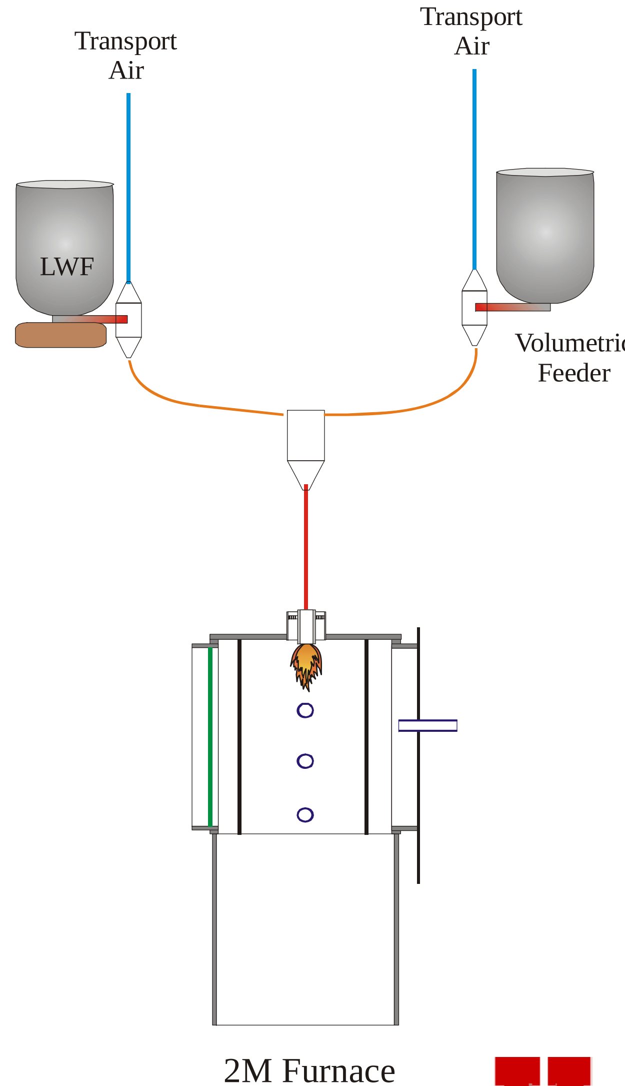
Initial Setup



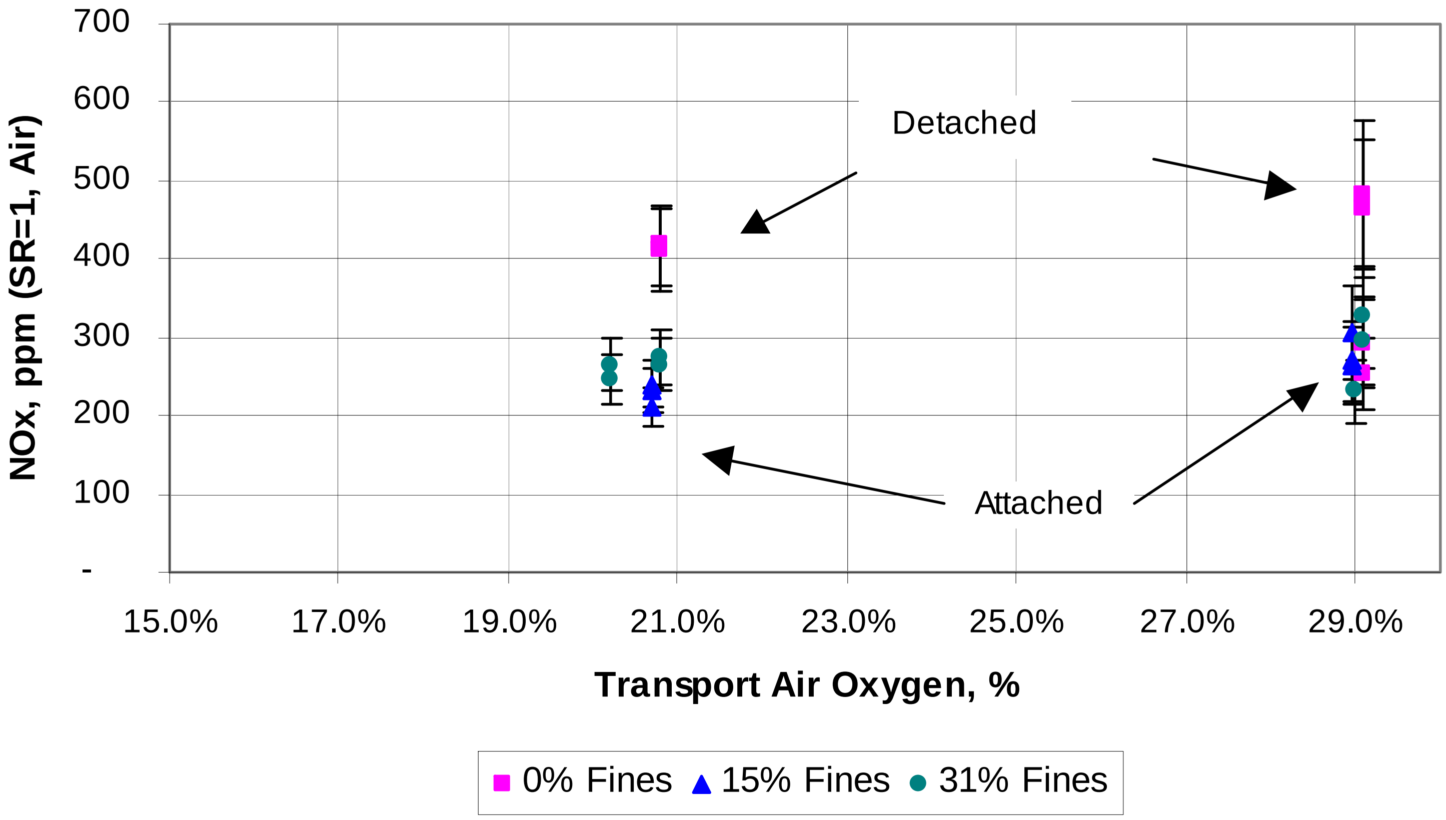
Blending



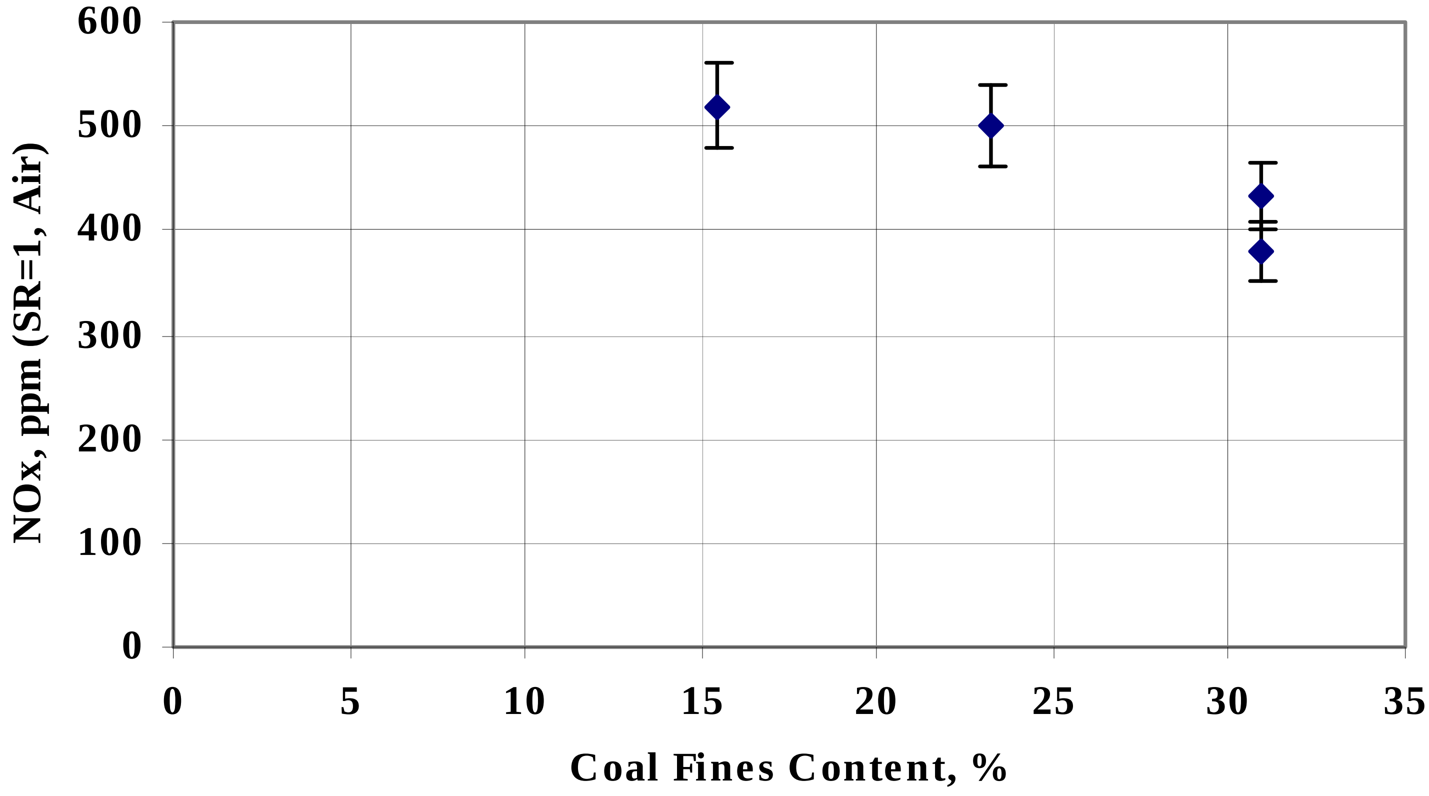
Co-Feeding



NO_x vs. Transport Air Oxygen



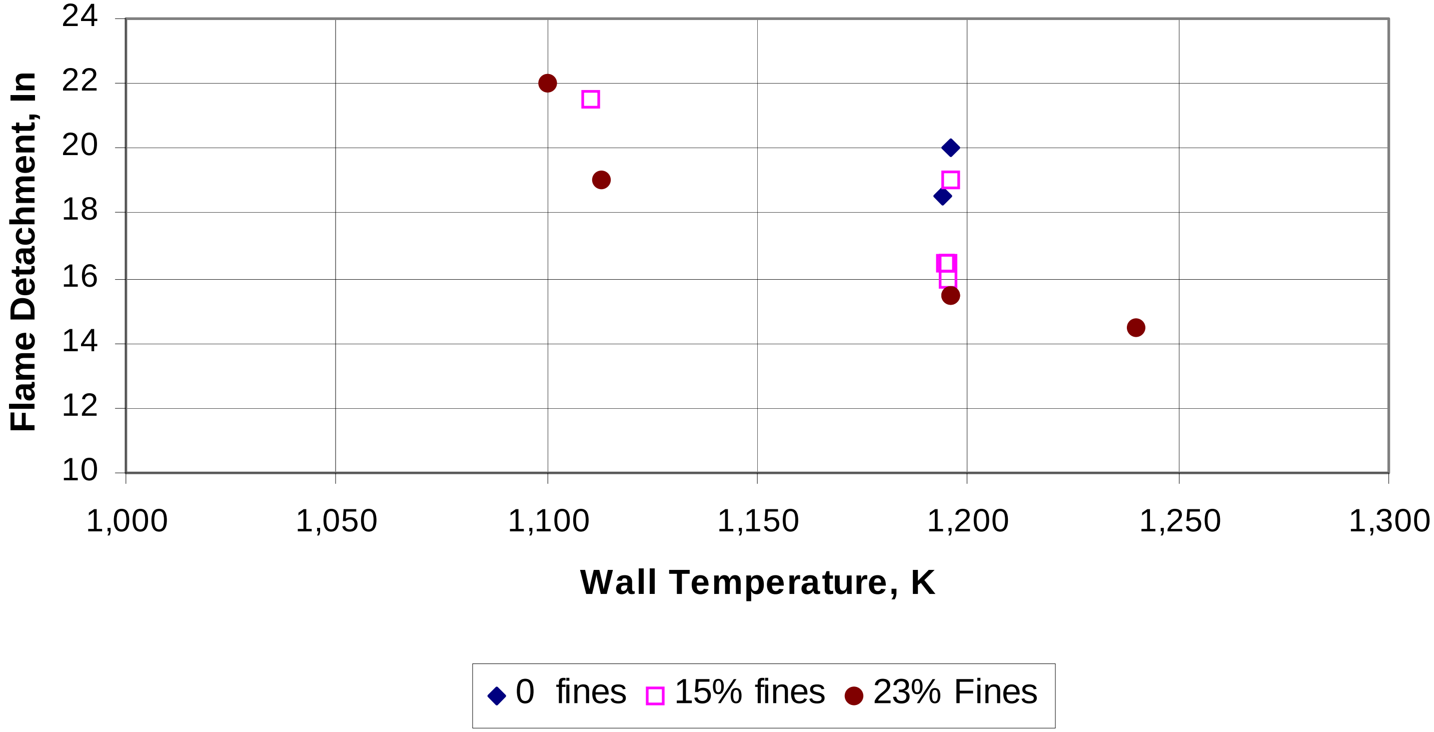
Fines vs. NO_x (attached flames)



Co-Feeding Base coal and Fines

THE UNIVERSITY OF UTAH

Fines Reduce Flame Detachment



21% Transport Air Oxygen

Conclusions: Axial diffusion flame furnace

- Demonstrated the utility of the 2m laboratory combustor in examining near-flame combustion phenomena.
  - Full-length quartz window
  - Electrically heated walls
  - Axial burner
  - Allows for *systematic adjustment* and evaluation of individual parameters

THE UNIVERSITY OF UTAH

Conclusions -Cont'd

- NO_x emissions reduced through flame attachment
  - Up to 64% reduction
- Promote flame attachment by increasing
  - Transport air Po_2
  - Fines
  - Wall temperature

Conclusions (Model B furnace)-Cont'd

- For always-attached flames
  - Po_2 had only slight effect on NO_x
- For always-detached flames
  - Increasing P_{O2} reduced flame detachment
  - Slight increases in Po_2 promoted flame stability
  - Increasing P_{O2} allowed otherwise detached flames to become attached and thus lower NOx
  - Produced stable detached flames

THE UNIVERSITY OF UTAH


قف


停

THE UNIVERSITY OF UTAH

Stability of axial pulverized coal flames under oxy-coal combustion conditions

Back Up – Additional Slides

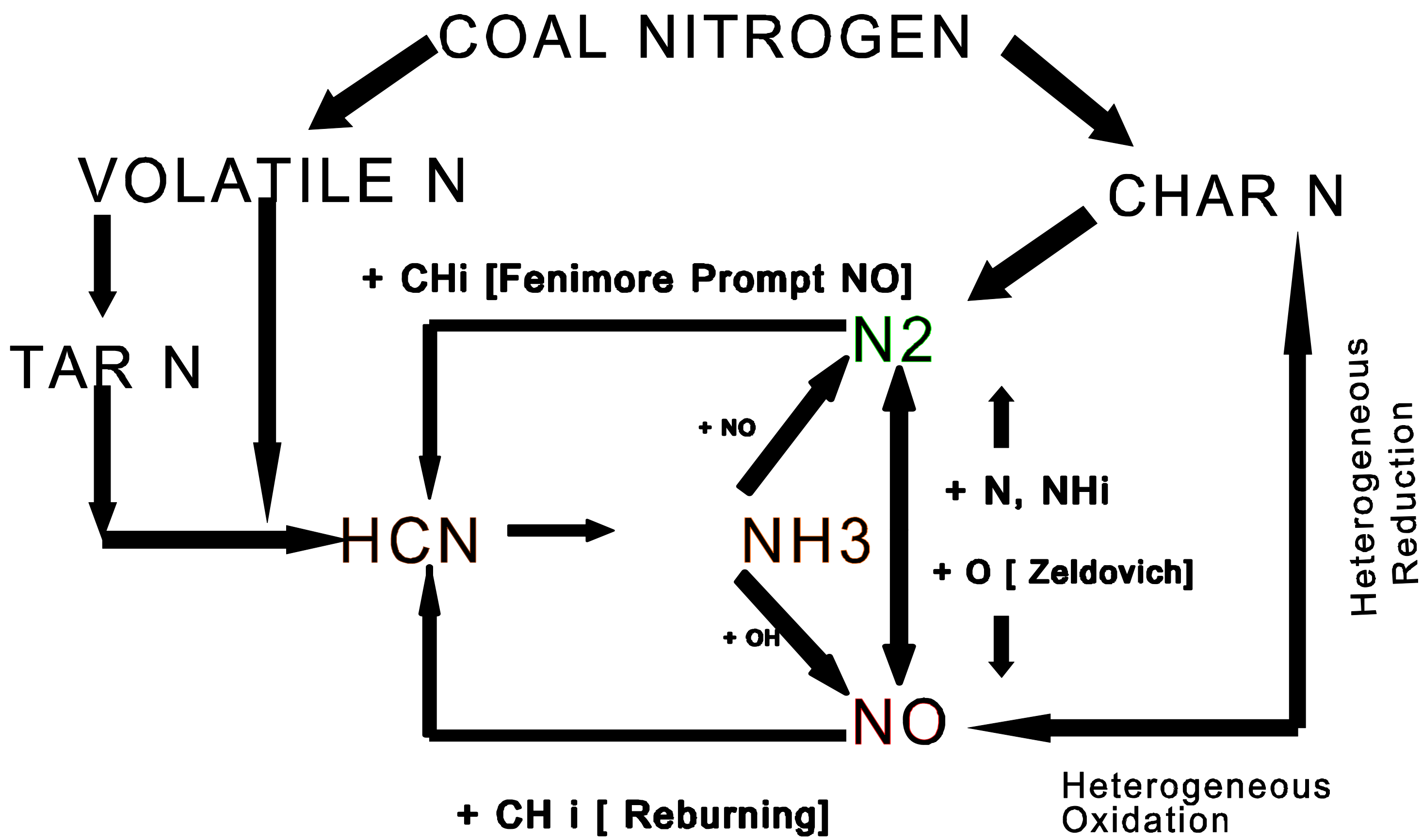
Related research on oxy-coal combustion:

Kinetic issues: *premixed* staged combustion (reactor mode – *no* diffusion flame)

- Studies on down fired laboratory furnace firing ~2kg/h coal.
  - Model A: reactor mode for kinetic issues.
- O_2 enrichment and staged combustion of pulverized coal (Kinetic issues: Model A)

THE UNIVERSITY OF UTAH

Fuel NO_x pathways

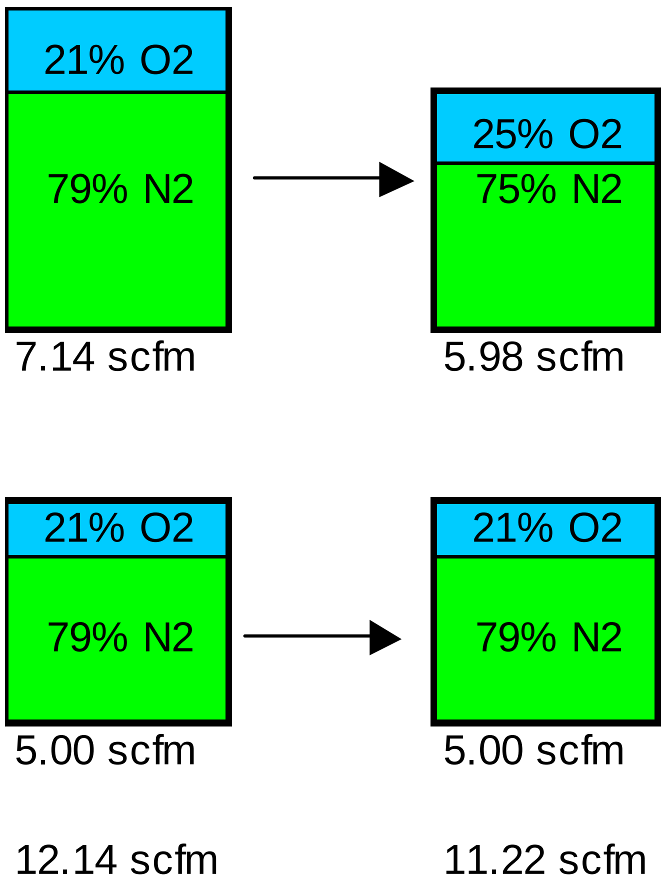


THE UNIVERSITY OF UTAH

Oxygen enrichment in staged combustion

2 kg/h coal

- First Stage
  - Remove 10% of the total air
  - Replace 10% O2 removed in first stage
- Second Stage
  - No change
  - All air removed in first stage

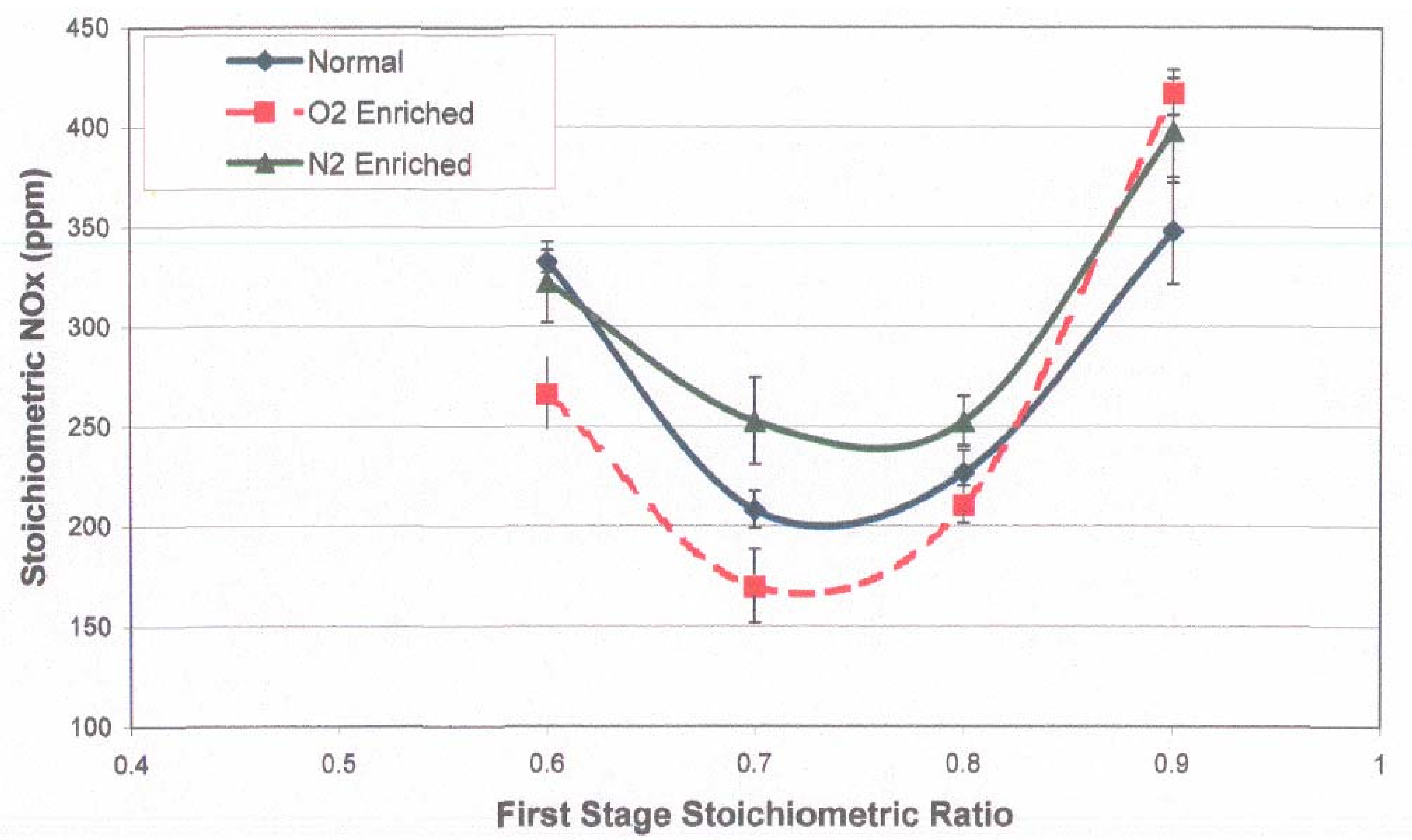


Flows are from a stoichiometric ratio of 1.2 overall, 0.7 in first stage.

THE UNIVERSITY OF UTAH

Kinetic Issues and O_2 enrichment addressed through experimentation on Model A laboratory combustor. Exhaust NO_x after staged combustion of pulverized coal vs SR in the first stage.

SR_{PRIM} varied; $SR_{EXHAUST}$= 1.2. Fixed staging location.



THE UNIVERSITY OF UTAH

IEA GHG International Oxy-Combustion Network

Pilot Scale Experiments Giving Direct Comparison Between Air and Oxy-Firing of Coals and Implication for Large Scale Plant Design

Windsor, CT, USA

25th, January, 2007

Toshihiko Yamada, IHI/Nobuhiro Misawa, J-Power

Contents

Oxy-fuel Pilot Scale Testing

Objectives

To confirm the following items during oxy mode combustion under the condition that is assumed to be the same heat transfer with air combustion mode.

- Heat transfer
- Flame temperature
- Combustion characteristics
- Ash characteristics
- Flame stability
- etc.

Oxy-fuel Pilot Scale Testing

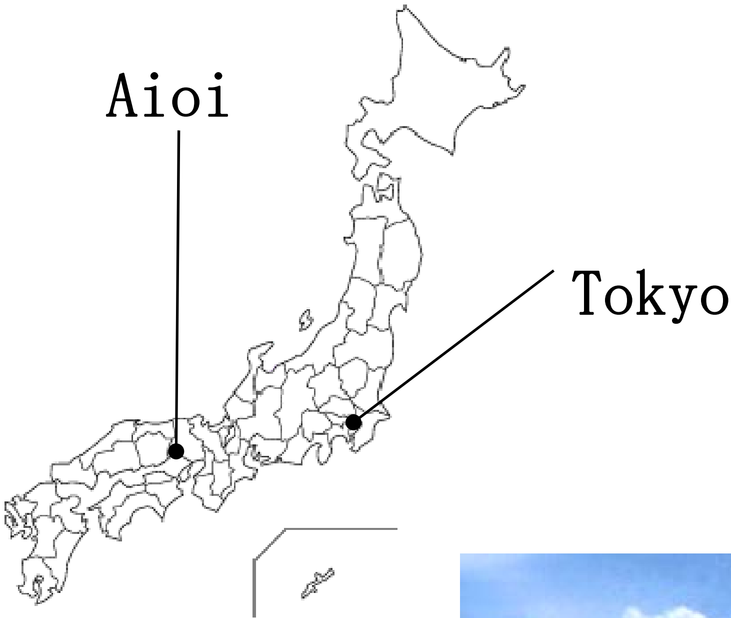


Photo of test facilities

IHI Aioi works

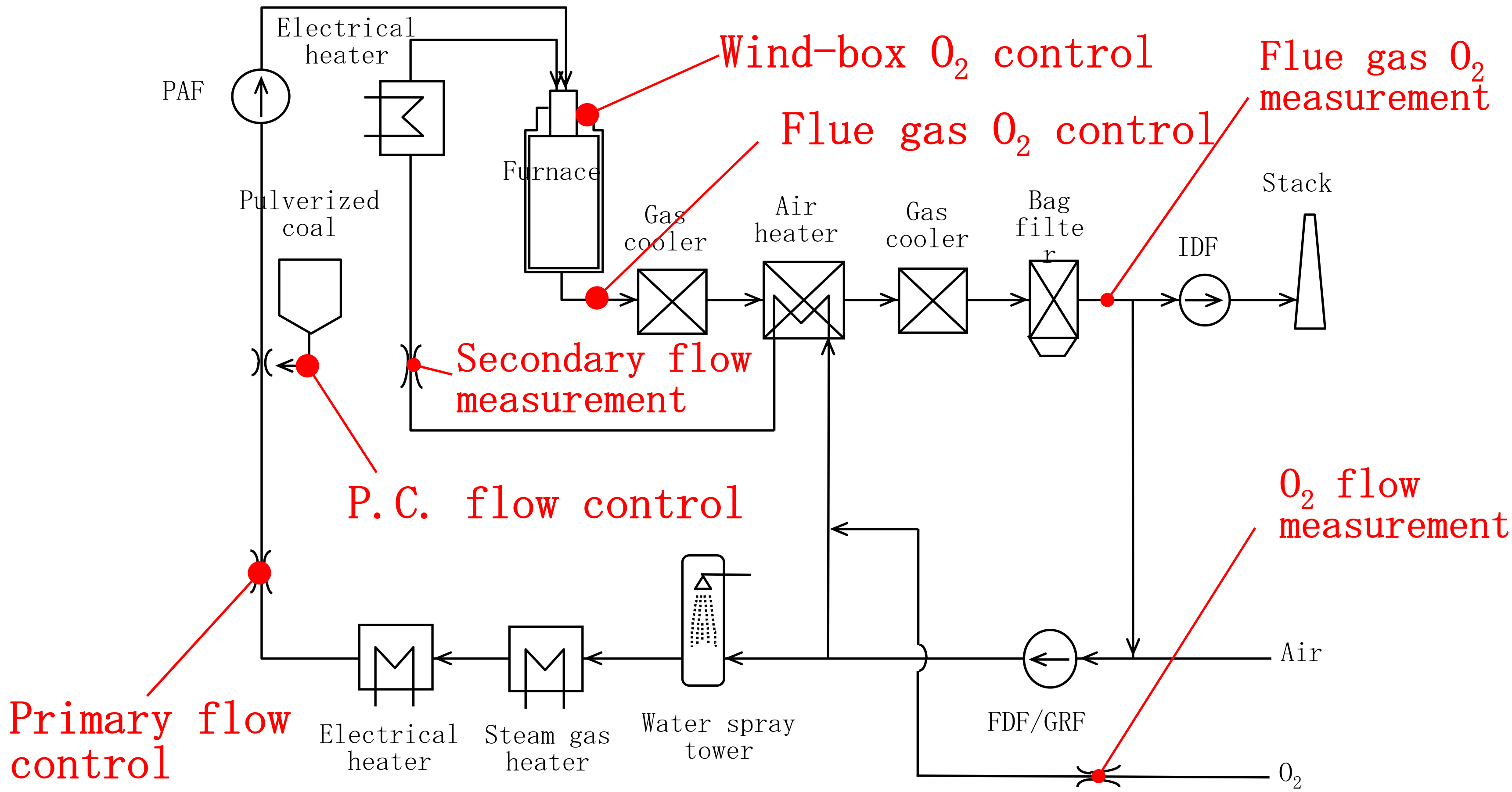
Oxy-fuel Pilot Scale Testing

Test facilities

Combustion Capacity: max. 150kg/h

Furnace: Vertical type / I.D. 1.3m × L 7.5m

Burner: Swirl pulverized coal burner



System configuration

Test conditions

Coal analysis

Coal	—	Coal A	Coal B	Coal C
HHV	[dry·MJ/kg]	23.7	27.9	30.0
Proximate analysis				
IM	[air dry%]	8.8	4.1	14.0
Ash	[dry%]	19.3	18.2	6.9
VM	[dry%]	25.7	40.9	34.1
FC	[dry%]	55.0	40.9	59.0
Ultimate analysis				
C	[dry%]	63.5	65.6	74.4
H	[dry%]	2.8	5.3	4.2
N	[dry%]	0.73	0.72	1.91
O	[dry%]	13.5	9.7	11.8
S	[dry%]	0.24	0.57	0.88

Combustion conditions

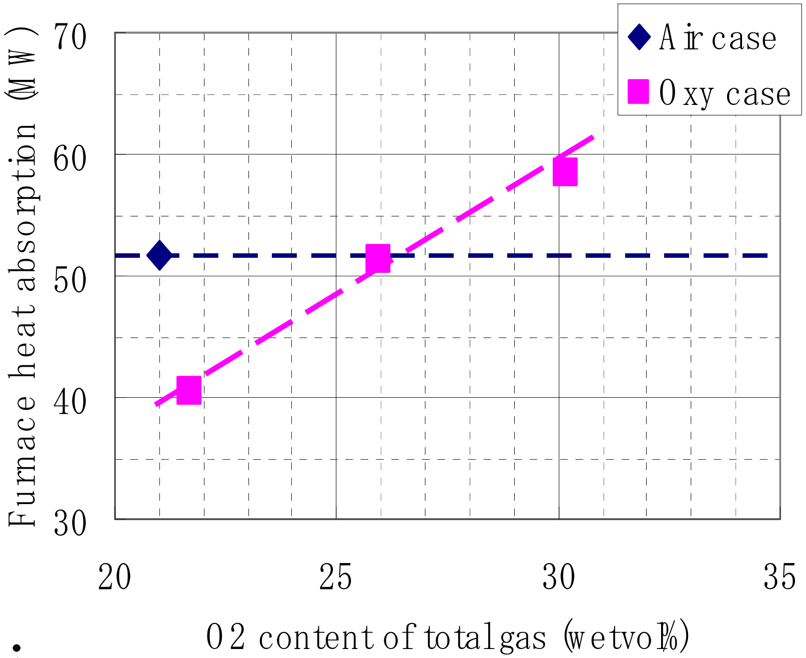
Combustion mode	—	Air mode	Oxy mode
Heat input	MWt	0.8 – 0.48	
Fineness	% under 74μm	75	
Flue gas O_2 at AH inlet	dry%	3.5 – 4.3	
Wind-box O_2	wet%	21 (Air)	35
Primary O_2	wet%	21 (Air)	3.5 – 4.3
Total O_2 content to furnace	wet%, calc	21 (Air)	27

*Without staging

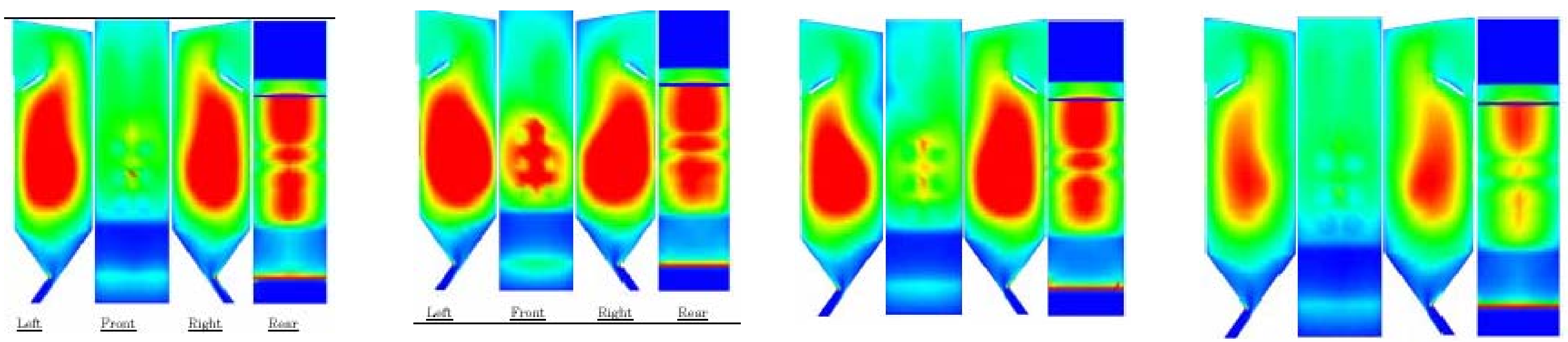
Application Study to Callide-A Power Plant

Furnace simulation

	Air	Oxy 1	Oxy 2	Oxy 3
Total gas flow	142t/h	117t/h	140t/h	170t/h
Total O_2 conc.	21%	30.2%	26.5%	21.7%
FEGT	Base	Lower	Nearly equal	Higher
Heat absorption	Base	Higher	Nearly equal	Lower

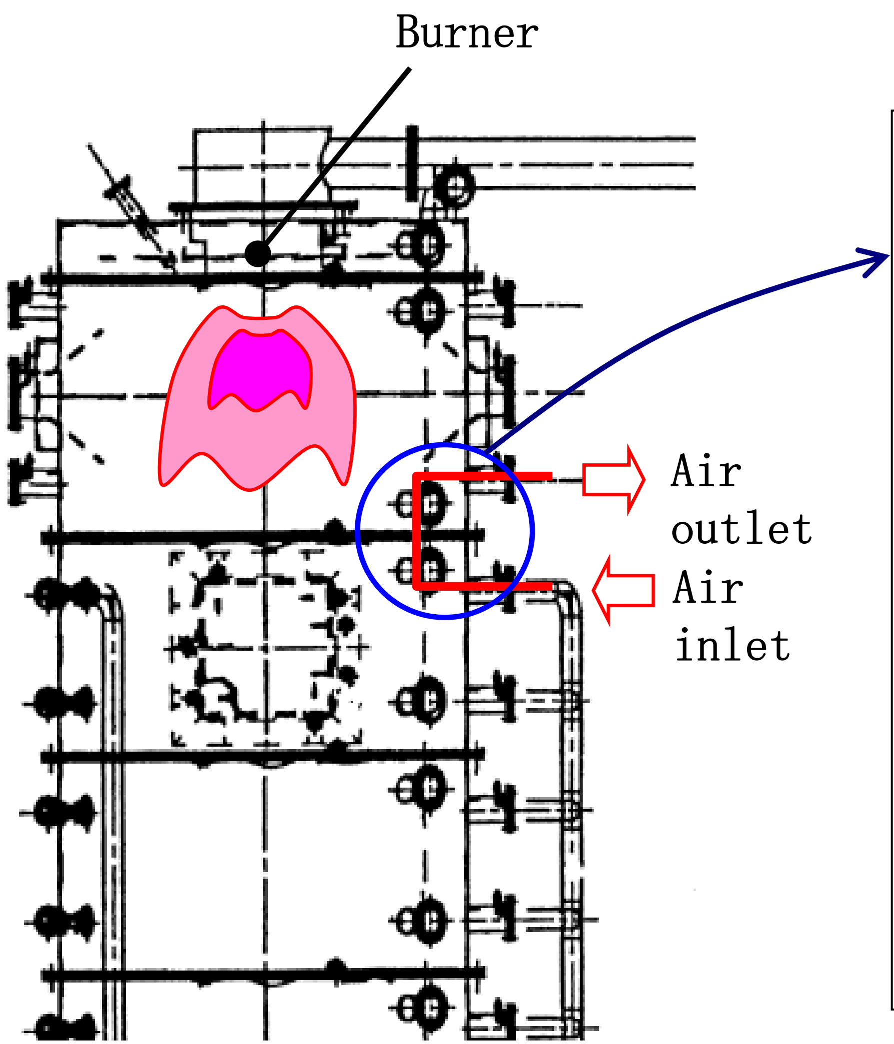


Simulation results of heat absorption



Air   Oxy 1   Oxy 2   Oxy 3

Heating elements during pilot-testing

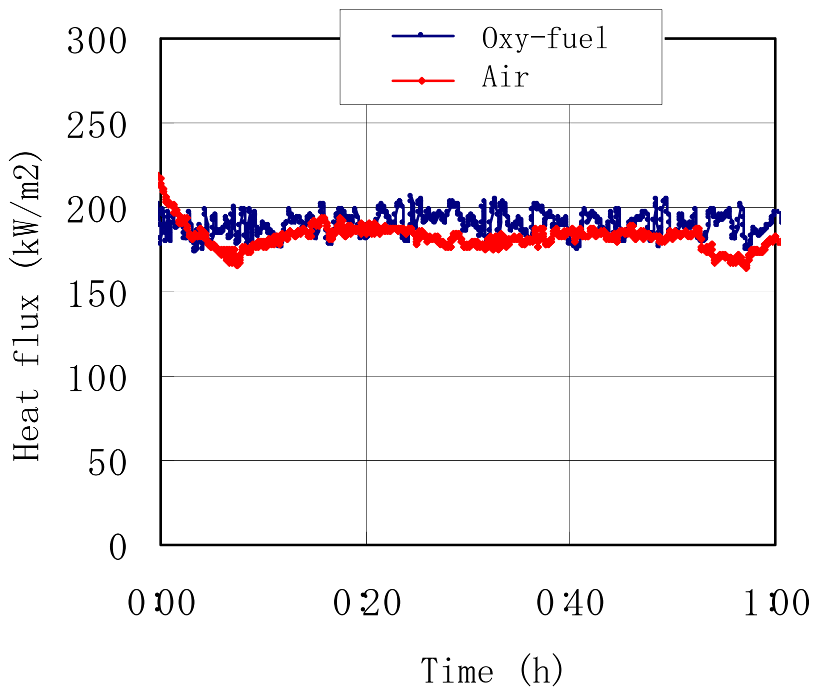


Furnace

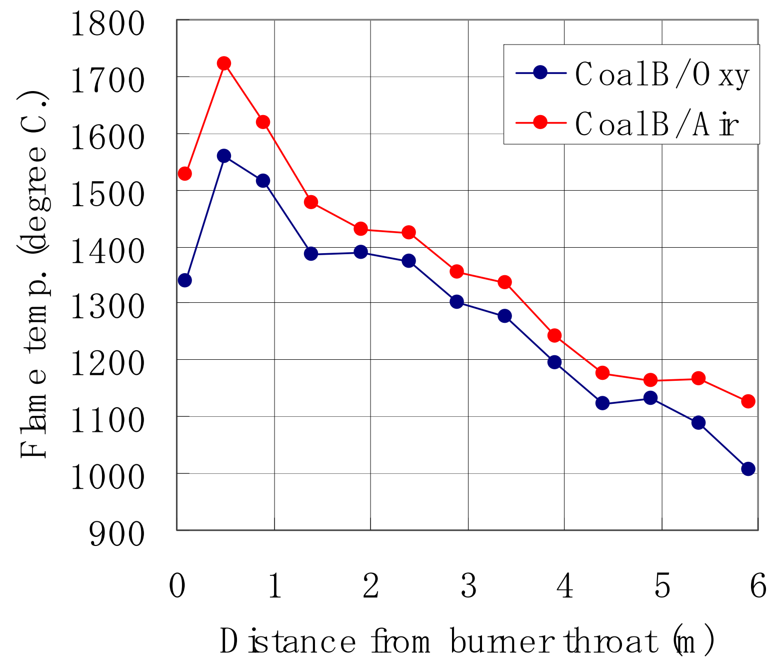
Heating elements at radiation section

Heat transfer and flame temperature

Heat flux at the radiation section



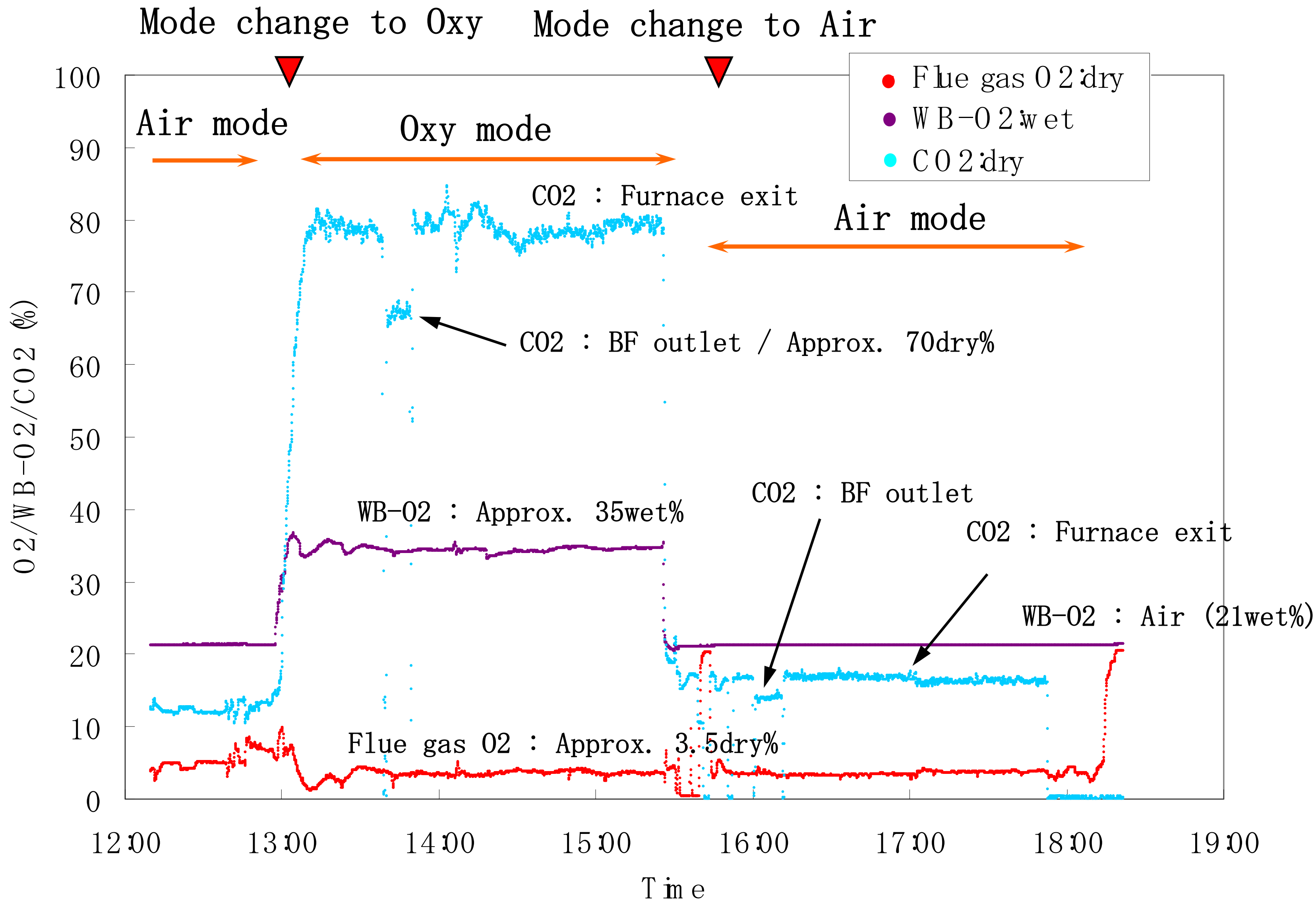
Flame temperature



Experimental results shows the same heat flux both air and oxy combustion mode

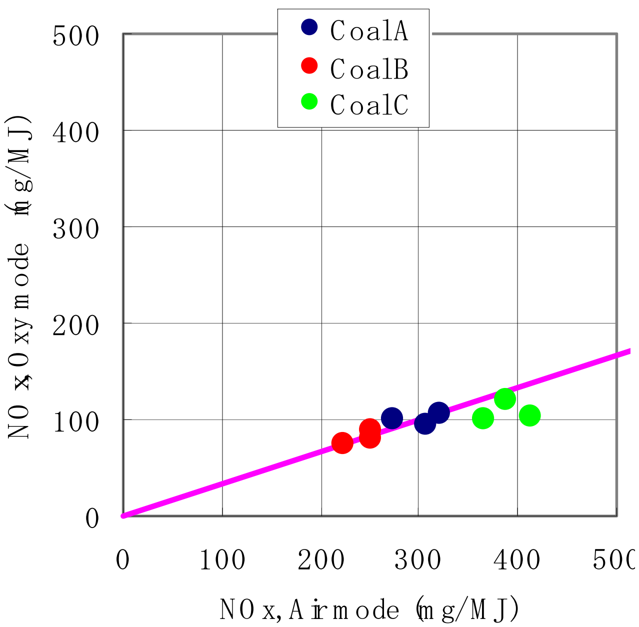
Operation data & CO2 concentration

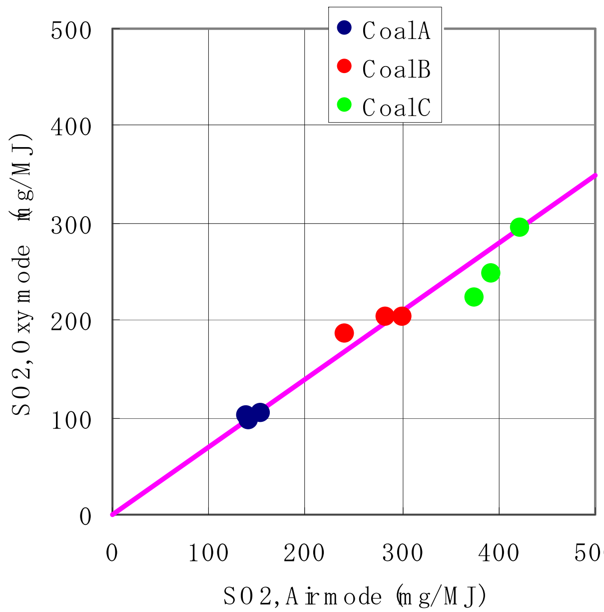
*Negative furnace pressure

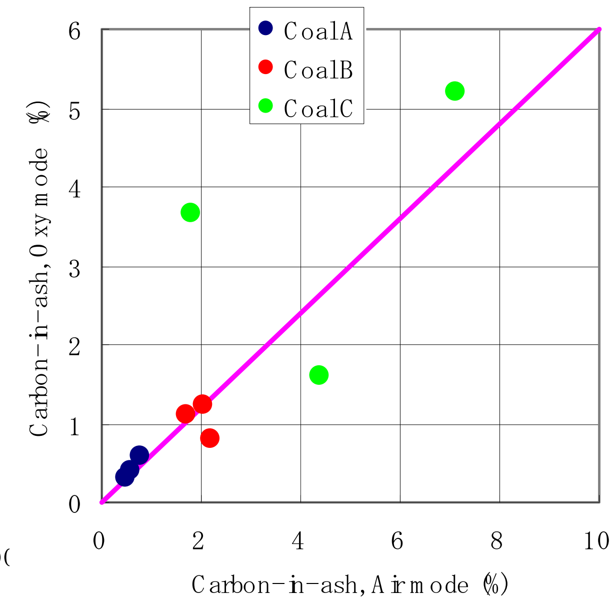


Combustion characteristics

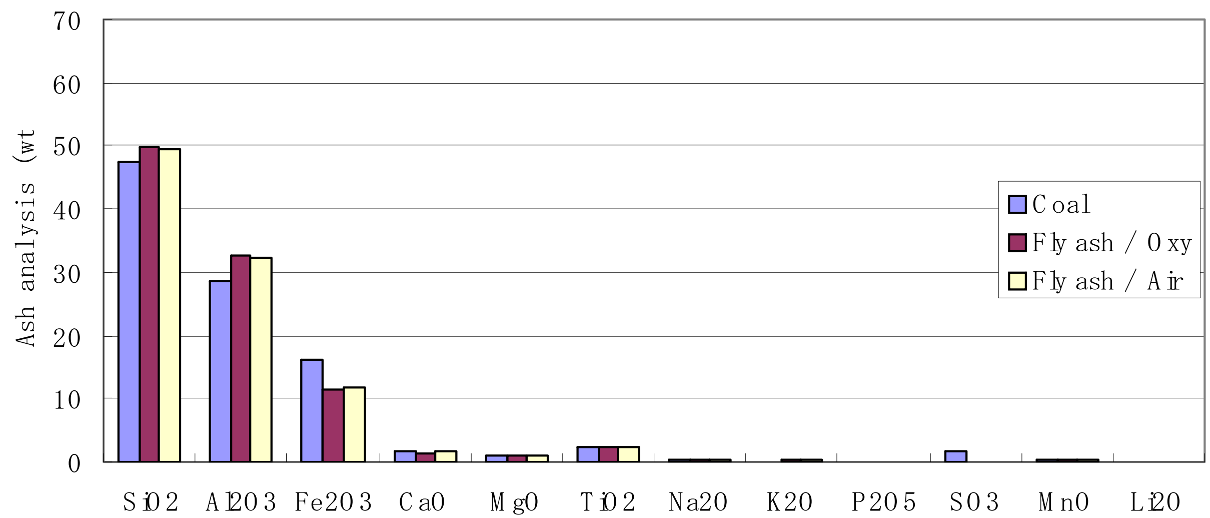
Combustion characteristics







Ash characteristics (coal A)



Combustion characteristics in oxy mode

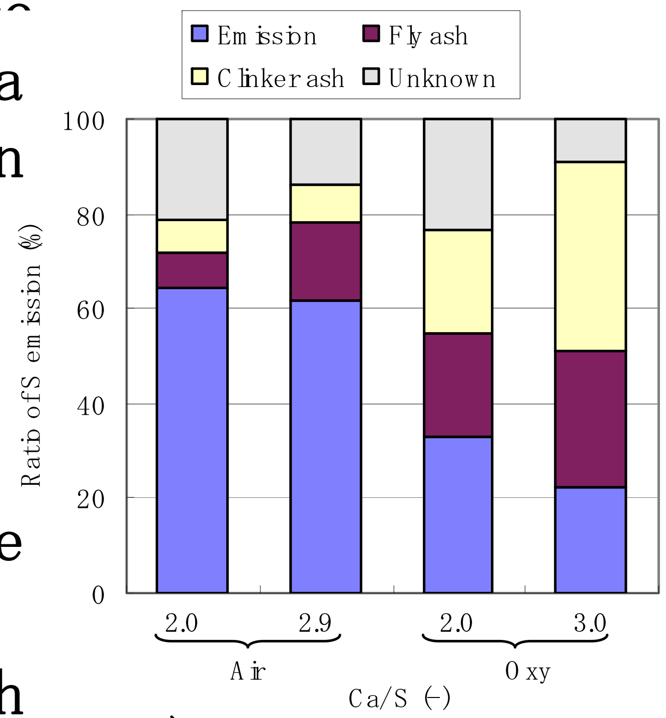
CO_2 : Approx. 70 dry% CO_2 will be expected in case of negative furnace pressure.

NOx : Concentration without staging is almost same in both mode. Emission in oxy mode is 60 - 70% reduction due to the decomposition of NOx in the recirculation gas in the flame.

SO_2 : Concentration in oxy mode is a few time. However, emission in oxy mode is 30% reduction due to the moving to the ash.

Carbon-in-ash:Carbon-in-ash is 30 - 40% lower in oxy mode due to the long residence time in the furnace.

Ash character : There is not so much different in both mode.



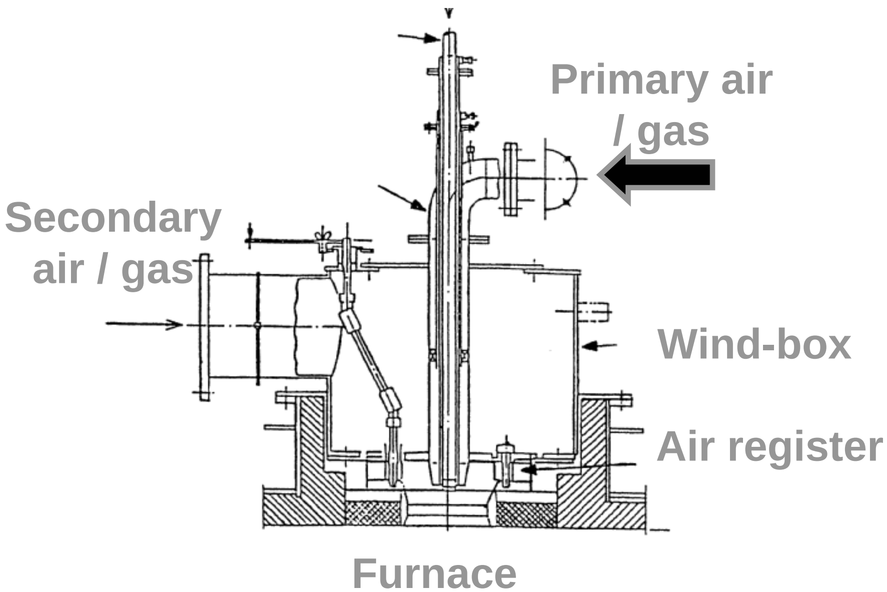
Ex.) Mass balance of S

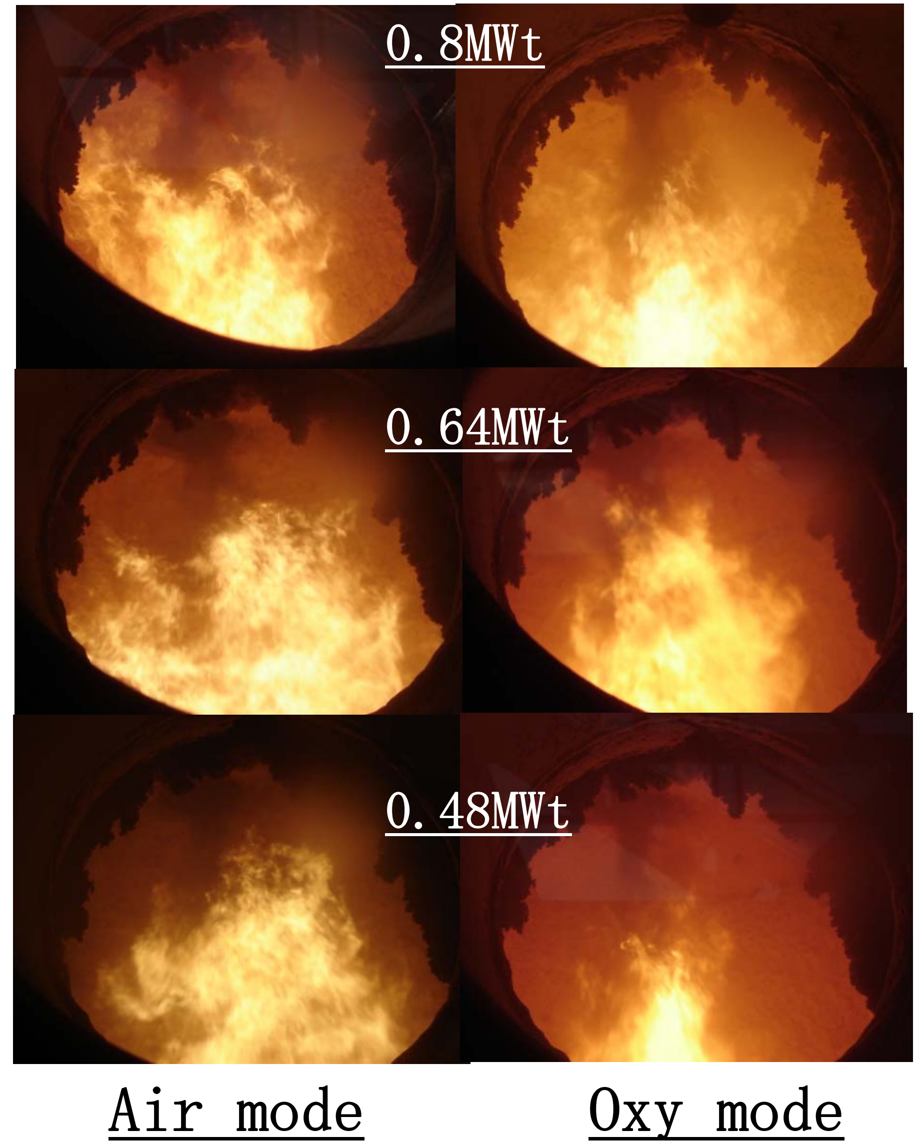
Flame stability

Flame stability

Flame is blown out from the burner throat at the burner low load operation.

*Direct O2 injection
*Limitation of low load





Implication

Implication for large scale plant from the test results, in case of the application to existing large-scale boiler.

<table>
<tr><th colspan="2">Items</th><th>Pilot-scale</th><th>Large-scale</th></tr>
<tr><td colspan="2">Heat transfer</td><td>Same heat absorption in the furnace at the approx. 27% of total oxygen to boiler</td><td>Probably same results</td></tr>
<tr><td rowspan="5">Combustion & ash character</td><td>CO2</td><td>Approx. 70 %</td><td>60 – 80 %</td></tr>
<tr><td>NOx</td><td>Same concentration / 60 – 70% emission reduction</td><td>Probably same results</td></tr>
<tr><td>SO2</td><td>A few time concentration / 30% emission reduction</td><td>Probably same results</td></tr>
<tr><td>Carbon-in-ash</td><td>30 – 40% reduction</td><td>Probably same results</td></tr>
<tr><td>Ash</td><td>Same character</td><td>Probably same results</td></tr>
<tr><td colspan="2">Flame stability</td><td>Flame is blown out at the low load, approx. 60%L.</td><td>Load limit or consideration of some kind</td></tr>
</table>

6. Summary

Summary of Oxy-fuel Pilot Scale Testing

*Simulation is the effective method to confirm the heat absorption.
*Total O_2 to the boiler during Oxy would be considered to be around 27% in order to have the same heat absorption during Air.
*Flame during Oxy is different with air at the burner low load operation because the gas volume to the boiler is reduced.
*CO_2 conc. will be expected to be 60 – 80 %
*Combustion characteristics are clear, that is NOx, SO_2, H_2O, Carbon-in-ash, ash characteristics etc..
*Necessity of direct O_2 injection would be considered in order to support the flame at low load operation, or plant operation without low load would be considered during Oxy.

Acknowledgement

These studies for the demonstration project were greatly supported by NEDO, JCOAL and J-Power as well as by Australian organizations such as CCSD, CS Energy, University of Newcastle and others.

-- Thank you for your attention!! --

Coal Particle Ignition, Devolatilisation and Char Combustion Kinetics during Oxy-Combustion

Christopher Shaddix, Jeff Murphy, and Alejandro Molina

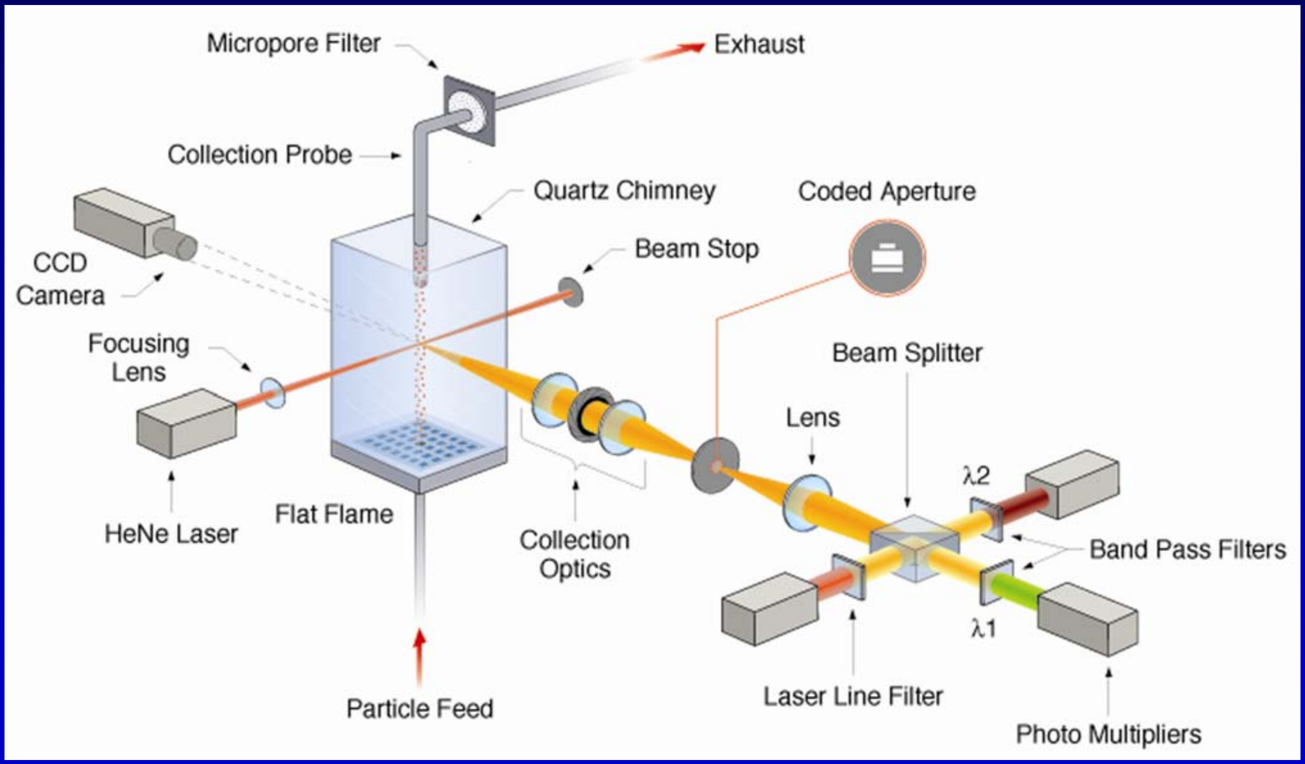
Combustion Research Facility
Sandia National Laboratories
Livermore, CA 94550

2nd Workshop
IEA GHG International Oxy-Combustion Network
Windsor, CT USA
January 25–26, 2007

Motivation for Bench-Scale Studies of Oxy-Combustion

- **Better control of important variables:**
  - **T**
  - **velocity**
  - **local gas mixture ([O_2], [CO_2])**
  - **τ_{res}**
  - **etc.**
  - **– allowing clear identification of governing phenomena**
- **Ability to apply advanced diagnostics to give better insight into processes**
- **Ability to quantify rate parameters for use in CFD models**

Experimental Setup: Combustion-Driven Optical Entrained Flow Reactor



- 1 atm
- compact, diffusion-flamelet burner
- coal or char particles introduced along centerline
- quartz chimney
- coded-aperture, 2-color pyrometry diagnostic for char size, T, and velocity
- laser-triggered ICCD for single particle imaging

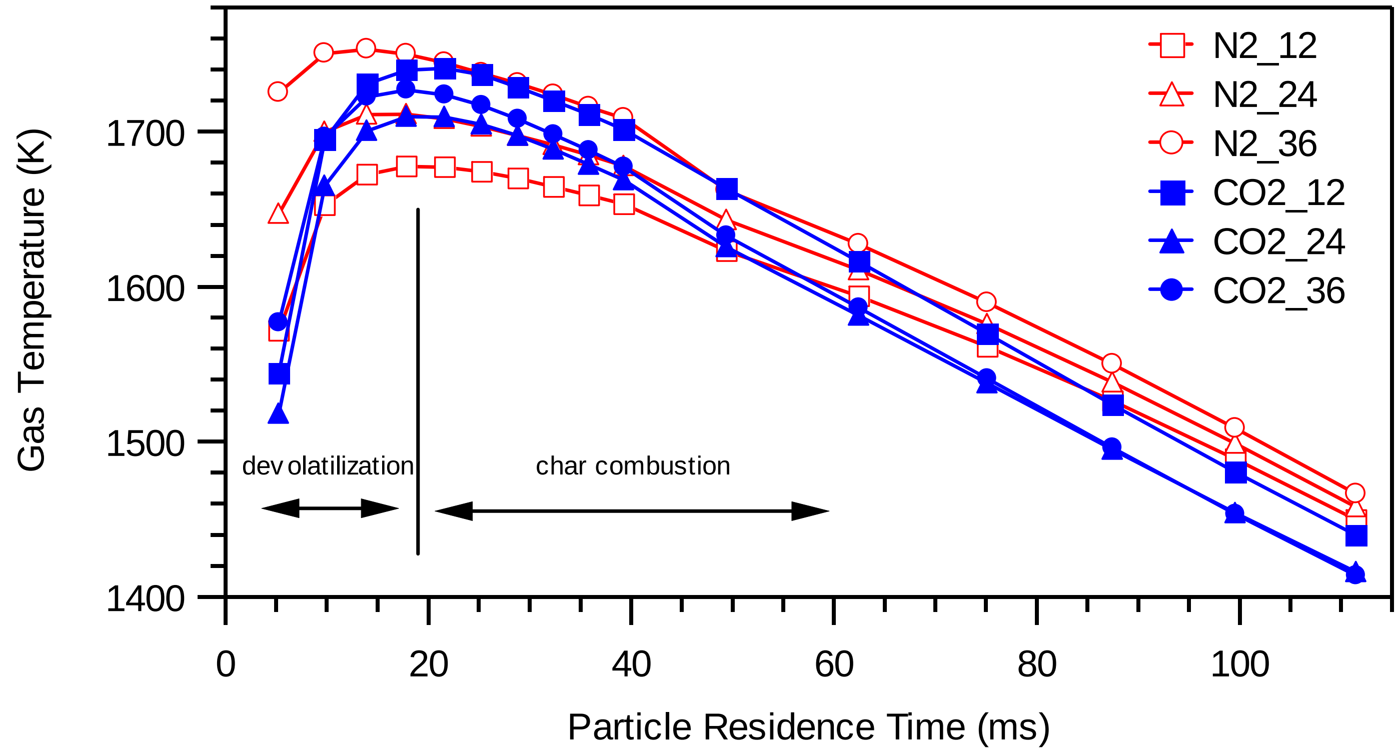
Oxy-Combustion Studies in SNL LEFR

- **Combustion of Pittsburgh hvb coal and Highvale subbit coal (106-125 μm) in 6-36 % O_2 in N_2 at 1400, 1600, and 1800 K**
  - char kinetics determined
  - nonlinear regression used to optimize fits for different kinetic expressions
- **Ignition of individual particles of Pittsburgh hvb coal and Black Thunder subbit coal (75-106 μm) in 12-36% O_2 in N_2 and in CO_2 at 1250 K and 1700 K**
  - measured time to ignition and duration of devolatilisation
  - soot and char particle temperatures measured
- **Combustion of Pittsburgh hvb coal and Black Thunder subbit coal (75-106 mm) in 12-36% O_2 in N_2 and in CO_2 at 1700 K**
  - currently deriving char kinetics

EFR Gas Compositions Investigated

Composition (%)	Operating Condition					
	N_2_12	N_2_24	N_2_36	CO_2_12	CO_2_24	CO_2_36
O_2	12.0	24.0	36.0	12.0	24.0	36.0
N_2	70.0	58.0	45.9	0.0	0.0	0.0
CO_2	4.0	4.0	4.1	74.0	62.0	50.0
H_2O	14.0	14.0	14.0	14.0	14.0	14.0

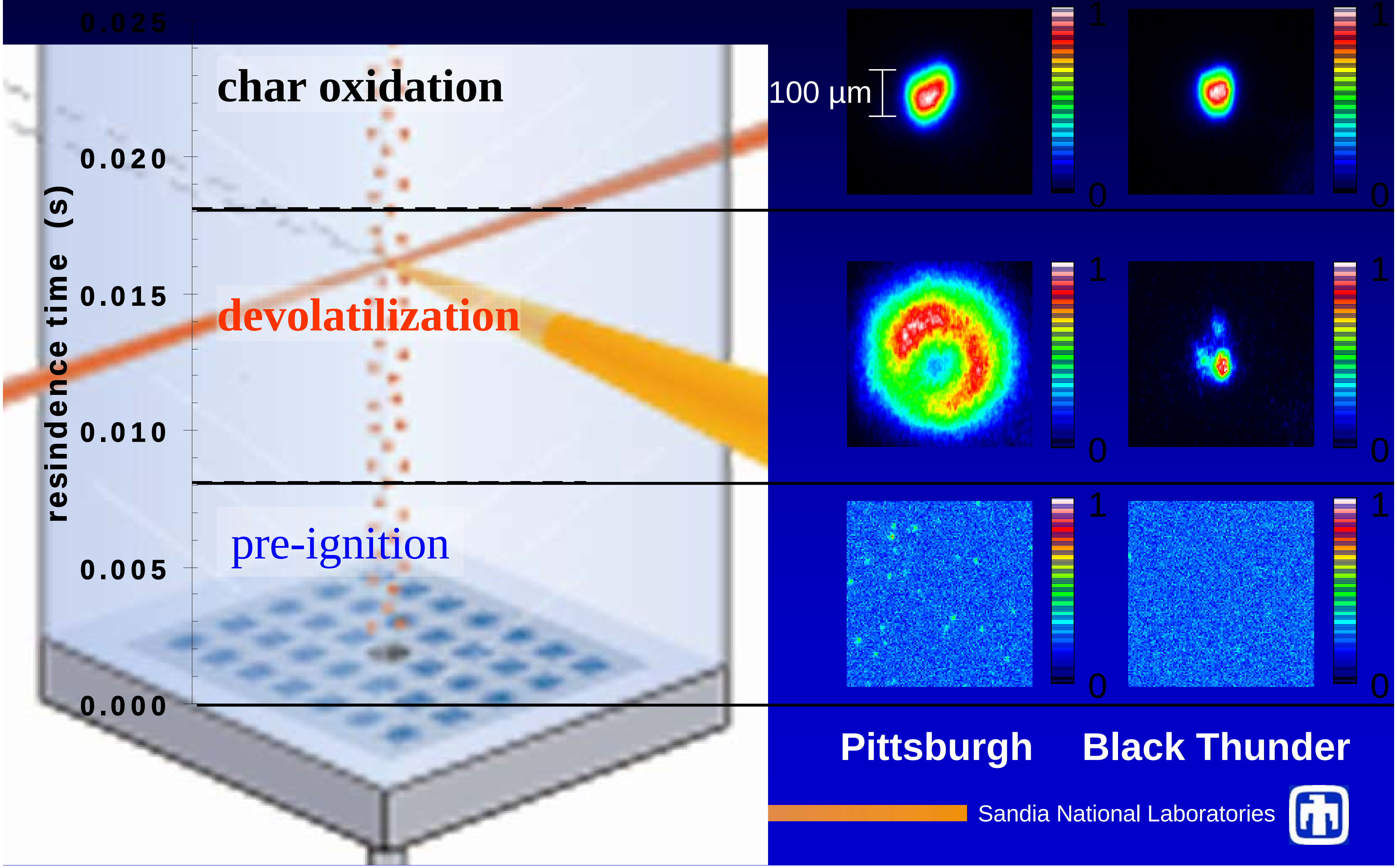
Gas Temperature Profiles



About the Gas Temperatures

- **CO_2 has a significantly greater (1.6 X) molar specific heat than nitrogen (and oxygen)**
- **For combustion in CO_2 environments, flame temperatures are lower (for a given initial O_2 concentration)**
  - CH_4/air adiabatic flame T = 2226 K
  - CH_4/O_2-CO_2 (21% O_2) adiabatic flame T = 1783 K
  - CH_4/O_2-CO_2 (32% O_2) adiabatic flame T = 2226 K
- **In our studies we *independently* vary concentrations of O_2, CO_2, and T (i.e., we're focusing on *microscale* effects, rather than trying to immediately jump to application)**

Single-Particle Imaging Studies



Sandia National Laboratories

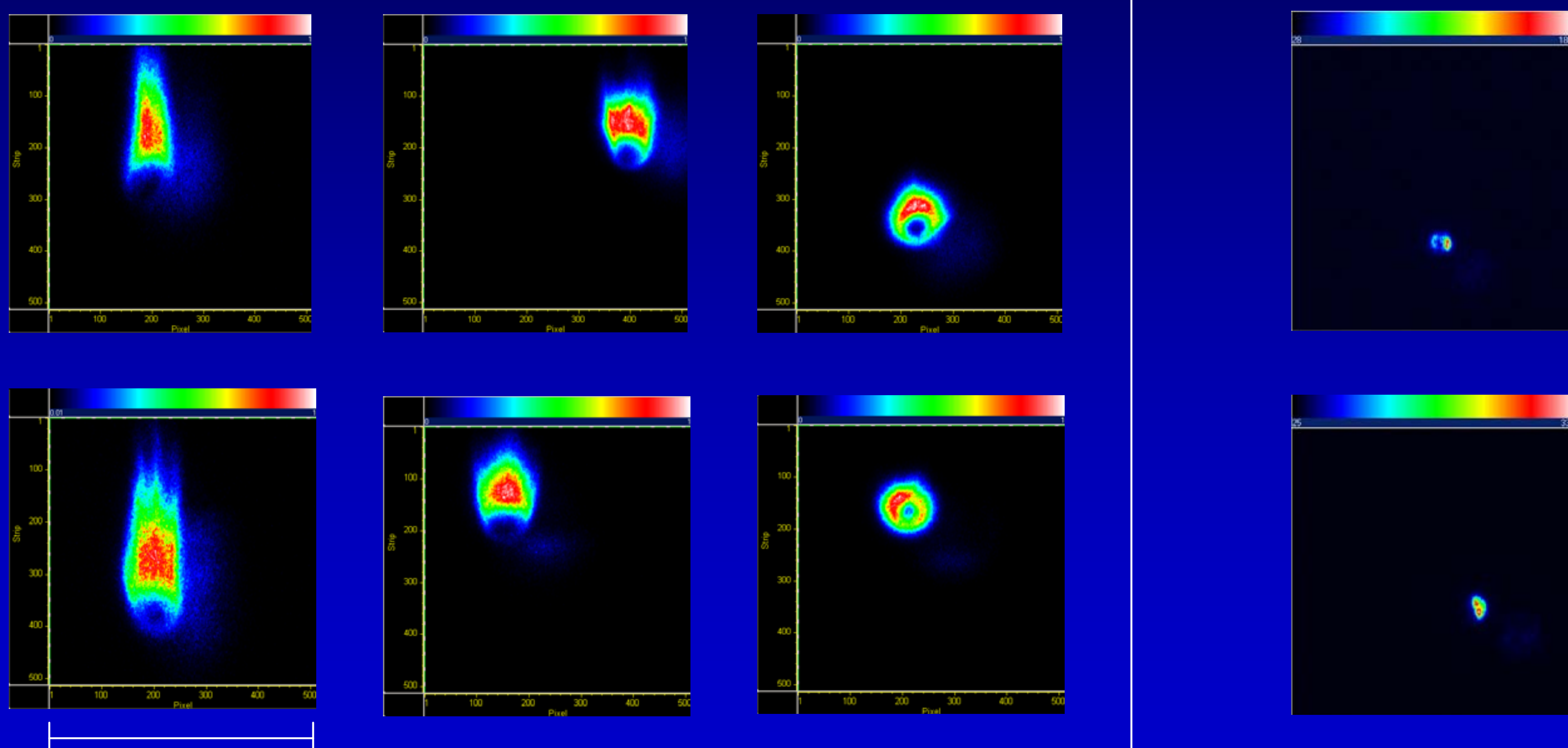
Effect of O_2 and N_2/CO_2 on Devolatilization

Pittsburgh Coal | **Black Thunder Coal**

12% O_2 | **24% O_2** | **36% O_2**

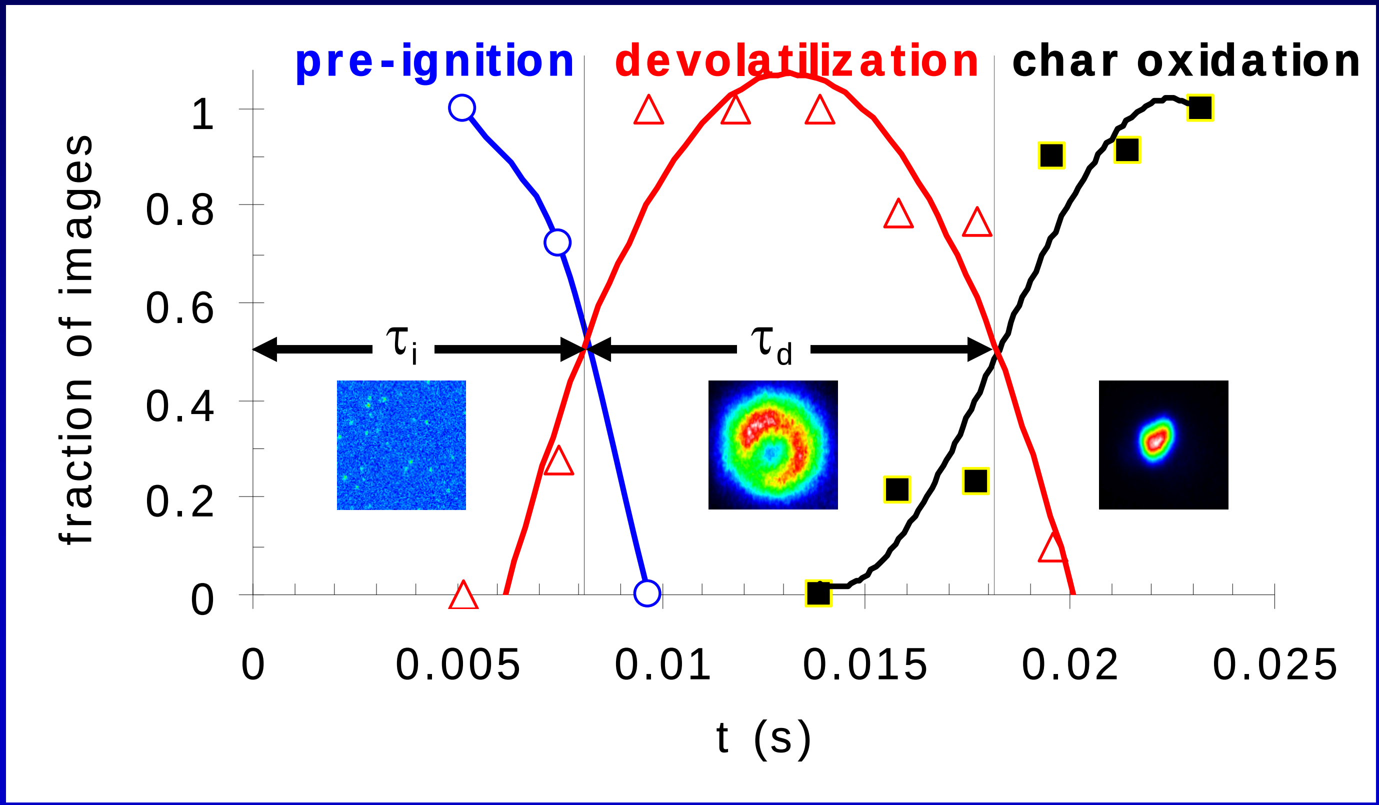
N_2

CO_2

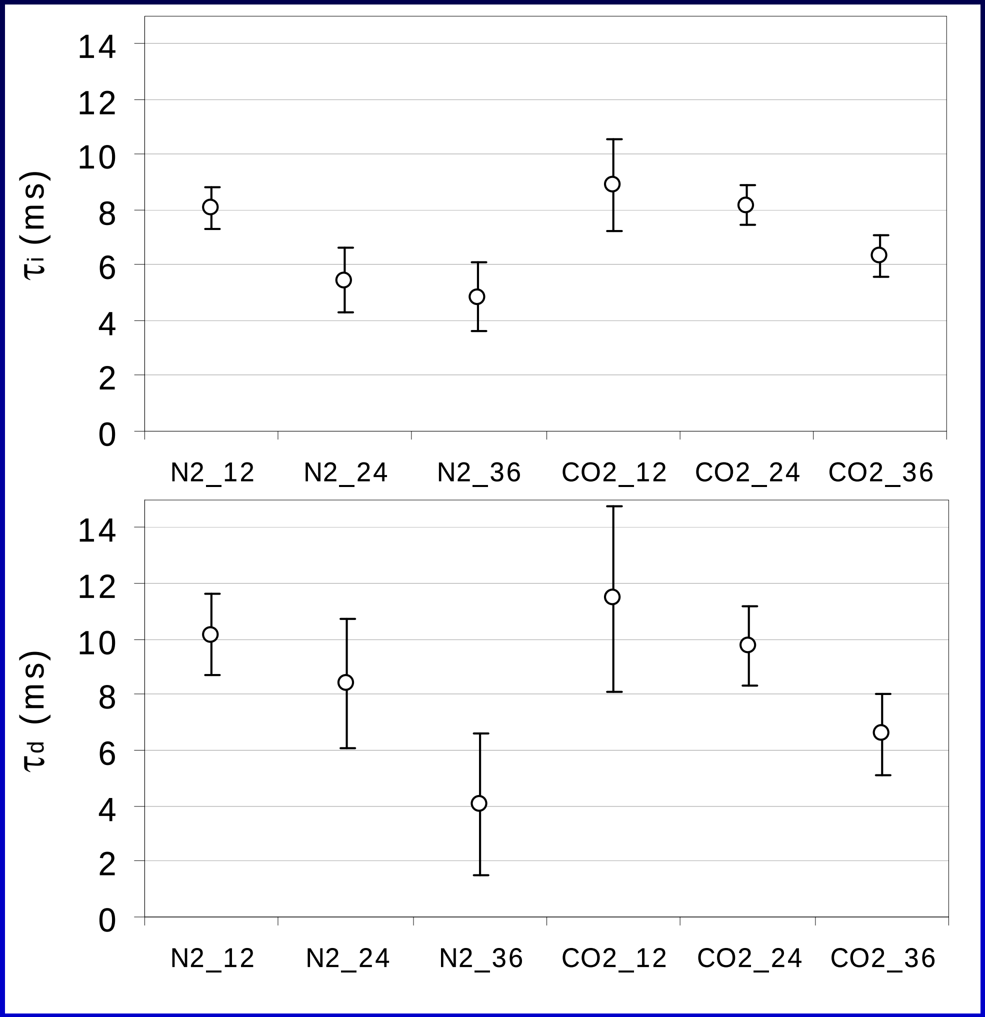


2.1 mm

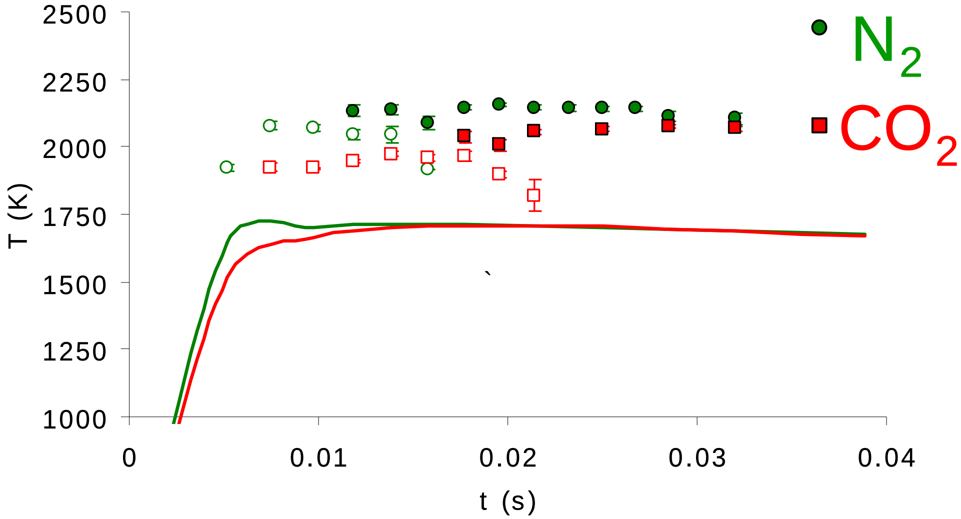
Quantifying Image Data: Characteristic Zones

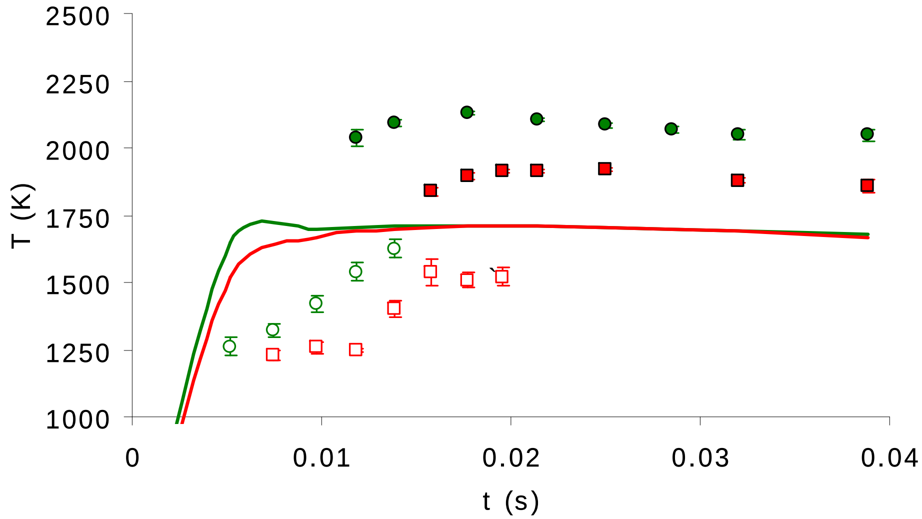


Ignition and Devolatilization Times: Pittsburgh Coal



Mean Temperatures: 24% O_2





Pittsburgh coal

Black Thunder coal

Understanding the Effects of O_2 and CO_2: Particle Ignition

- **Initial particle heat-up:**

$$\frac{dT_p}{dt} = \frac{-3}{C_{p,p}\rho_p r_p}\left[\varepsilon\sigma\left(T_p^4 - T_w^4\right) + h\left(T_p - T_g\right)\right]$$

- **h = k*Nu/d ; Nu ~ 2 ; $k_{CO2} \sim k_{N2}$**
- ***Initial heat-up should be independent of O_2 and CO_2***
- **Therefore, particle ignition differences due to homogeneous ignition process of volatiles in hot gas**
- **Dependent variables for homogeneous ignition are:**
  - reactivity of local mixture (O_2 effect)
  - combustion heat release (ΔH_{rxn})
  - ρC_p of local gas mixture (1.7 X larger for CO_2)

Understanding the Effects of O_2 and CO_2: Devolatilization Time

- **From droplet combustion theory:**

$$\dot{m} = 4\pi r_s \left(\rho_s D_{volatiles}\right)\ln\left(1+B\right)$$

where the Spalding transfer number is

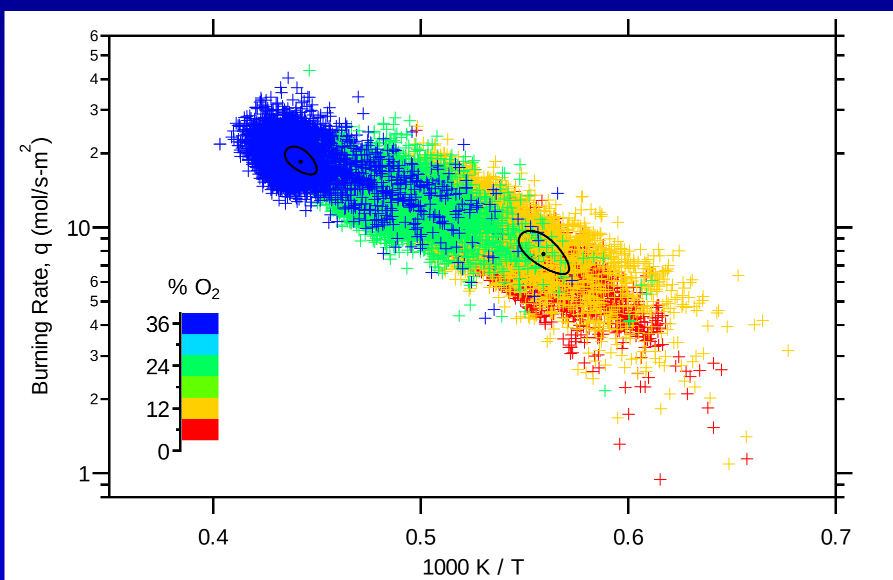
$$B = \left[C_{p,v}\left(T_\infty - T_s\right) + \left(Y_{o,\infty}/OF\right)h_c\right]/h_v$$

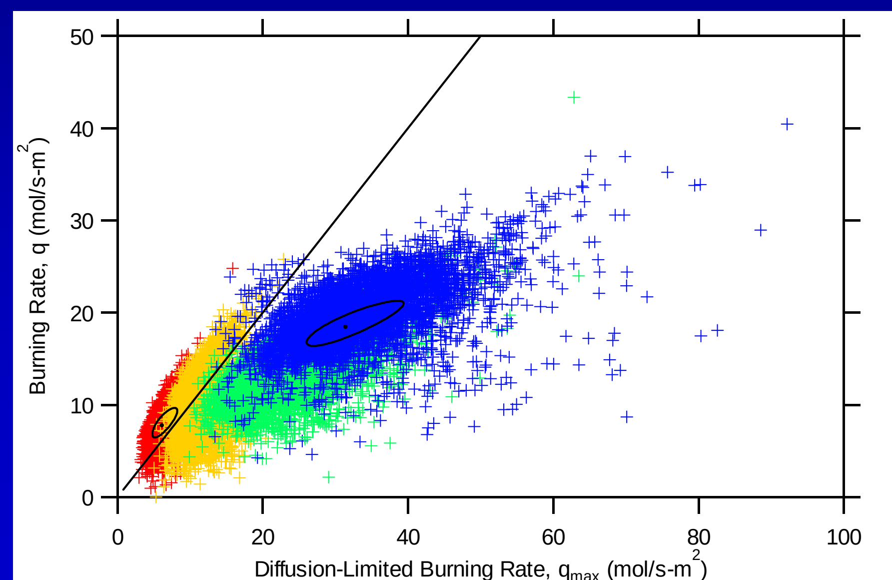
- **O_2 concentration feeds directly into Spalding transfer number**
- **mass consumption rate is lower in CO_2 because $D_{v,CO2} < D_{v,N2}$ (e.g., $D_{CH4,CO2} = 0.8 * D_{CH4,N2}$)**
- **differences in local flame radiation (from surrounding flame) may also play a role (ignored in droplet comb theory) – volatiles flame is hotter in N_2 environments but has CO_2 line emission in CO_2 environments**

Char Kinetic Study: O_2 Concentration

- **Data for different gas temps and oxygen concentrations blend together seamlessly**
- **Many particles at 6% O_2 and 12% O_2 burn in the diffusion limit; for higher O_2 levels particles move away from diffusion limit**

Pittsburgh coal





Char Kinetic Study: O_2 Concentration

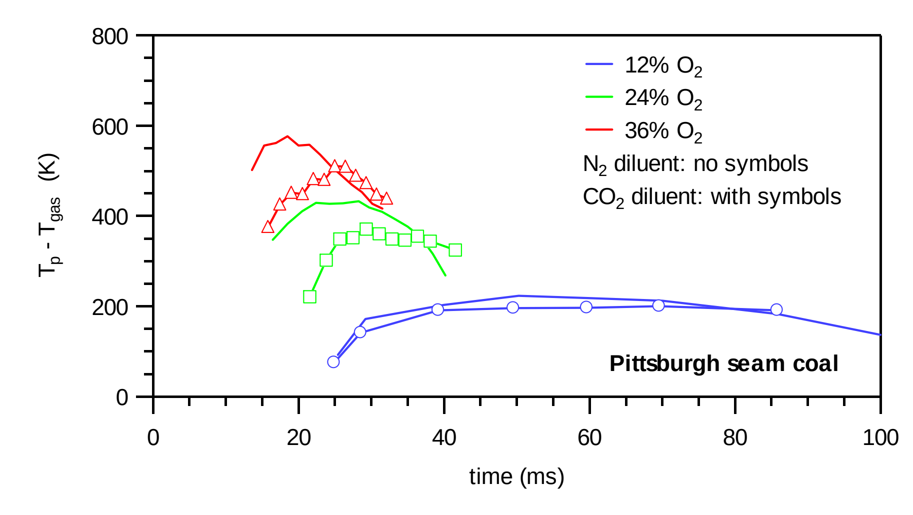
- **Fit of *n*th-order Arrhenius and *n*th-order Langmuir-Hinshelwood kinetic models to complete dataset (6%-36% O_2) yields low reaction orders in O_2 (*n* = 0.2-0.3)**

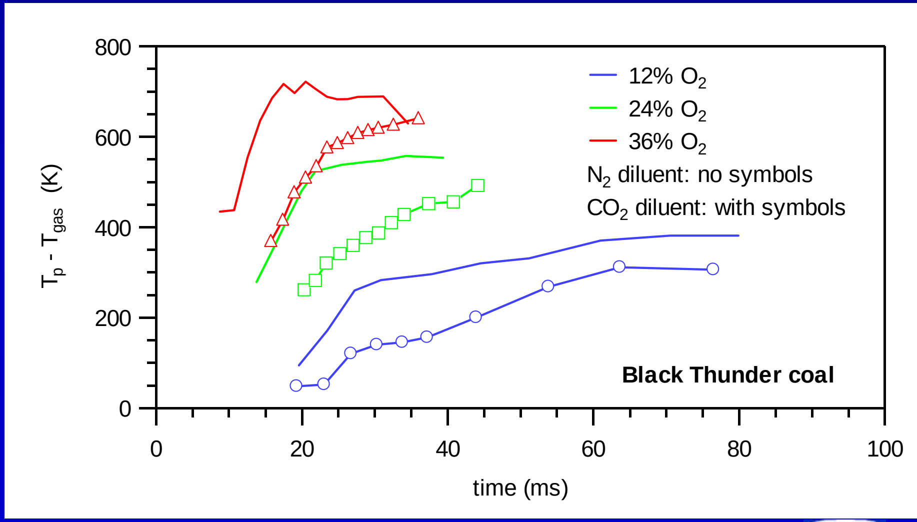
$$q = k_s p_{O_2,s}^n \qquad q = \frac{k_2 k_1 p_{O_2,s}^n}{k_1 p_{O_2,s}^n + k_2} \qquad k_s = A\exp\left(-E/RT_p\right)$$

- **Fit of *n*th-order Arrhenius model to 24% and 36% O_2 data yields *n* = 0.5, E_a ~ 80 kJ/mol**
- **Highvale coal is 30% more reactive than Pittsburgh**
- **For more details, see Murphy and Shaddix, *Comb. Flame* 144 (2006) 710-729.**

Char Kinetic Study: N_2 vs. CO_2

- Char combustion temperatures consistently lower in CO_2, implying lower char burning rate
- Bigger effect seen for Black Thunder coal
- Detailed kinetic analysis should shed some understanding





Conclusions

- Separate from the macroscale effects associated with overall flame T and radiant heat transfer, both O_2 and CO_2 concentrations affect single-particle ignition, devolatilization, and char combustion processes
- Oxygen effects are much stronger than CO_2 effects
- CO_2 effects on particle ignition and devolatilization appear to be understood
- Relative to air, microscale O_2/CO_2 effects on ignition and devolatilization approximately cancel each other out for 30% O_2 in CO_2 (similar to macroscale canceling)
- CO_2 appears to decrease char burning rate, but data require further analysis

Acknowledgments

- Research sponsored by U.S. DOE Fossil Energy Power Systems Advanced Research program, managed by Dr. Robert Romanosky, NETL

End of Presentation

Questions?

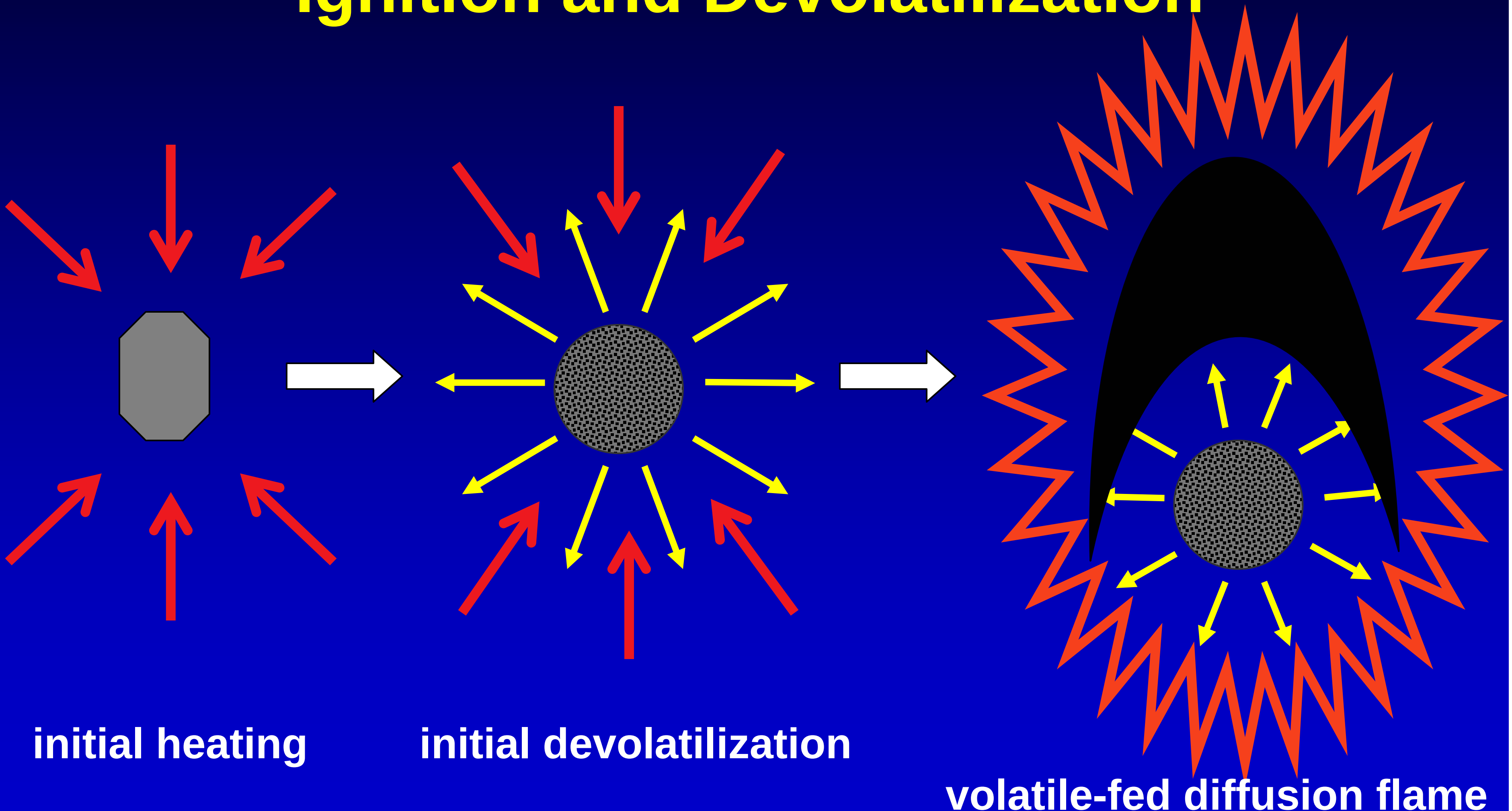
Coals Investigated

	Coal Type			
	Pittsburgh Bailey		Black Thunder	
Proximate	wt%, as rec'd	wt% dry	wt%, as rec'd	wt% dry
moisture	1.43		10.80	
ash	6.91	7.01	5.01	5.62
volatile	35.38	35.89	40.41	45.30
fixed C	56.28	57.10	43.78	49.08
Ultimate	wt% dry	wt% DAF[a]	wt% dry	wt% DAF[a]
C	77.20	82.93	60.90	64.11
H	5.19	5.58	5.18	5.45
O (by diff)	7.15	7.68	27.60	29.05
N	1.52	1.63	0.87	0.92
S	2.03	2.18	0.44	0.46

[a] dry, ash-free

Both coals were sieved to a 75–106 μm size fraction

Conceptual Model of Single-Particle Ignition and Devolatilization



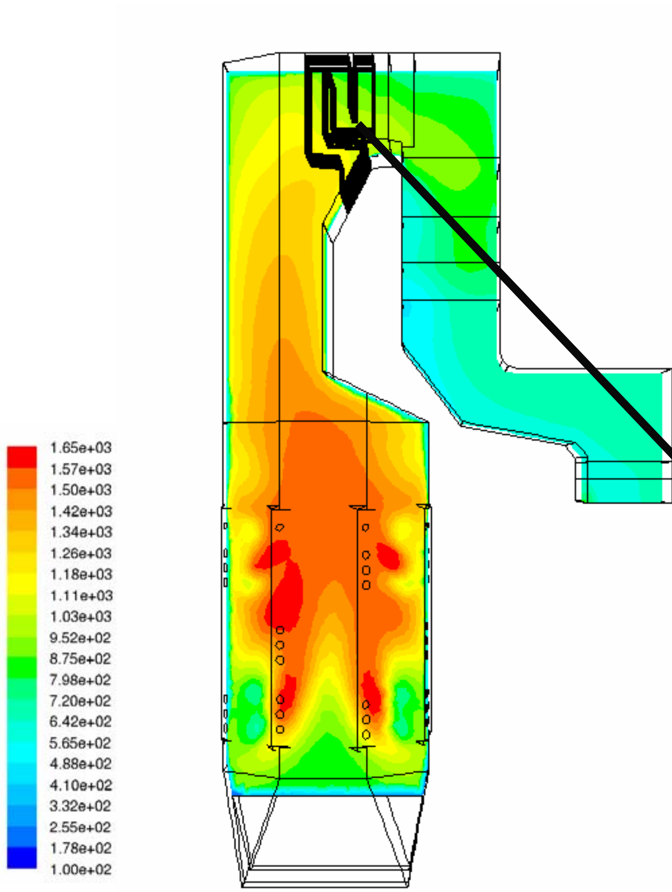
Coal Ignition Studies

- **Historically dominated by concerns over coal dust explosions and fire safety**
  – minimum gas T for ignition of particles or cloud (irrespective of ignition delay time)
  – minimum gas T for ignition decreases with increasing O_2 concentration
  – highly variable ignition T found depending on method of dust cloud preparation and injection
  – single-particle studies recommended for consistency
- **Few studies on pc ignition time in high temperature environment**
  – relevant criteria for burner operation
  – ignition times on order of 10 ms

CFD Modelling for Oxyfuel Combustion

Karin Eriksson
Vattenfall Research and Development, Sweden

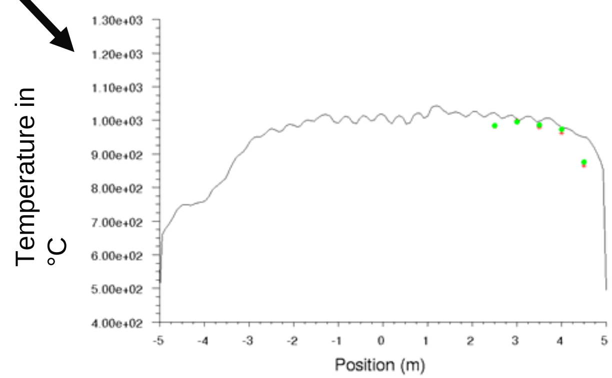
Background



Temperature in °C

CFD (Computational Fluid Dynamics) is today a useful tool for problem solving and optimization of air fired boilers.

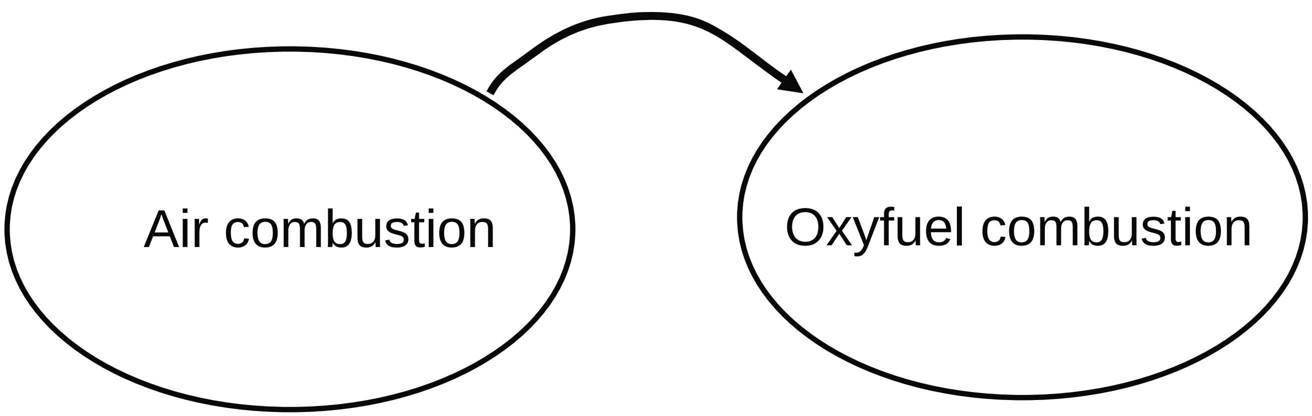
It is foreseen that the tool will be very useful also for oxyfuel combustion.



VATTENFALL

Model development necessary

The models used for combustion simulations in commercial CFD softwares are adopted to air combustion.



Development and validation of the submodels are necessary for oxyfuel combustion.

VATTENFALL

Main quantities to estimate

Heat transfer characteristics

Flame shape / flame length

Emissions and burnout

Oxidizing/reducing conditions along furnace walls

Submodels affected

Radiation modeling

- Gas radiation properties

Modeling of homogenous reactions

- Gas phase kinetics
- NOx mechanisms

Modeling of heterogeneous reactions

- Char combustion rates
- Gasification reactions

VATTENFALL

Validation of the models

Laboratory scale gas flames
20 kW natural gas (IVD)
80 kW propane (Chalmers)

→

Laboratory scale coal flames
20 kW coal (IVD)
80 kW coal (Chalmers)
500 kW coal (IVD)

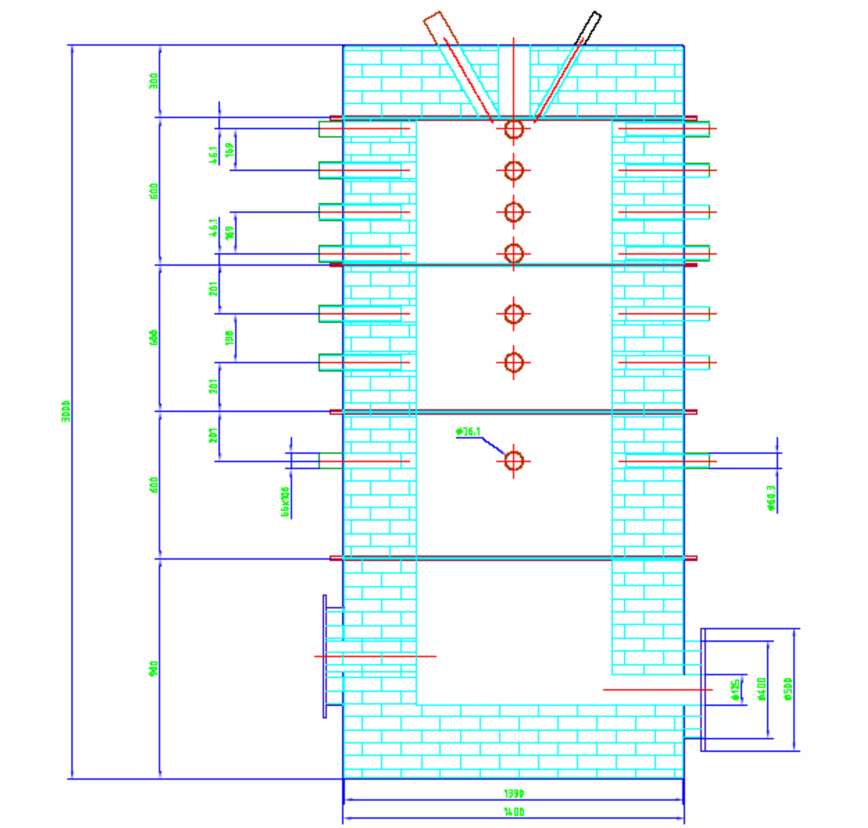
→

Pilot scale
30 MW

→

Full scale oxyfuel application

Validation case 80 kW propane flame [1]



80 kW propane flame, swirl burner

Cylindrical test furnace, top fired.

Height 2400mm; Diameter: 800 mm

Measurement access at 7 positions

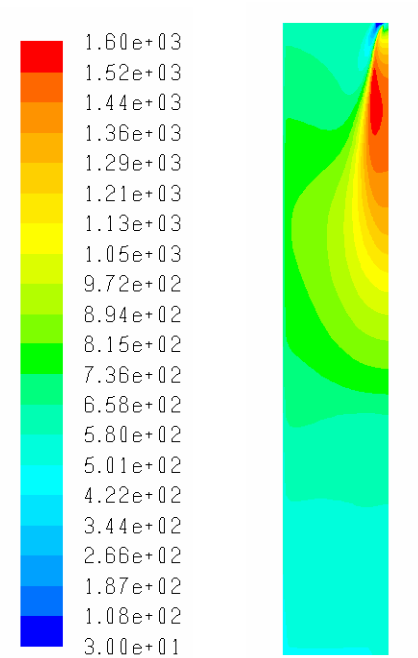
Isolated walls; 4 cooling loops

Both air and oxyfuel cases.

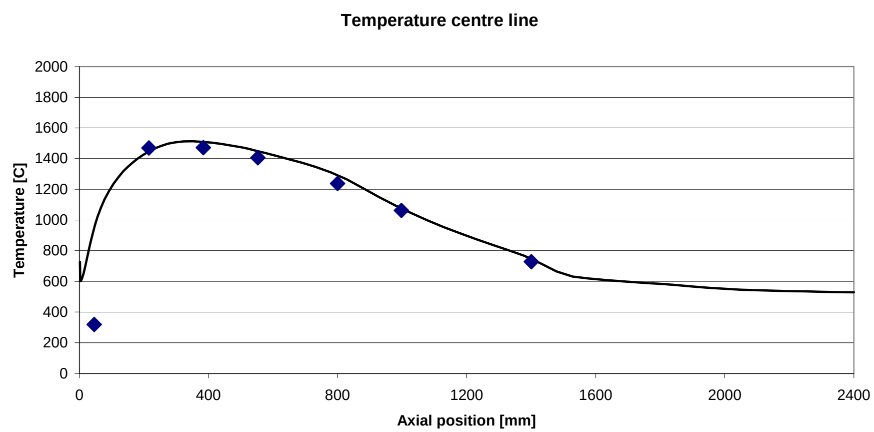
[1] Andersson, Klas; Carbon Capture for Fossil Fuel Power Plants using O2/CO2 Recycle Combustion Process; Lic Thesis Chalmers University of Technology 2005

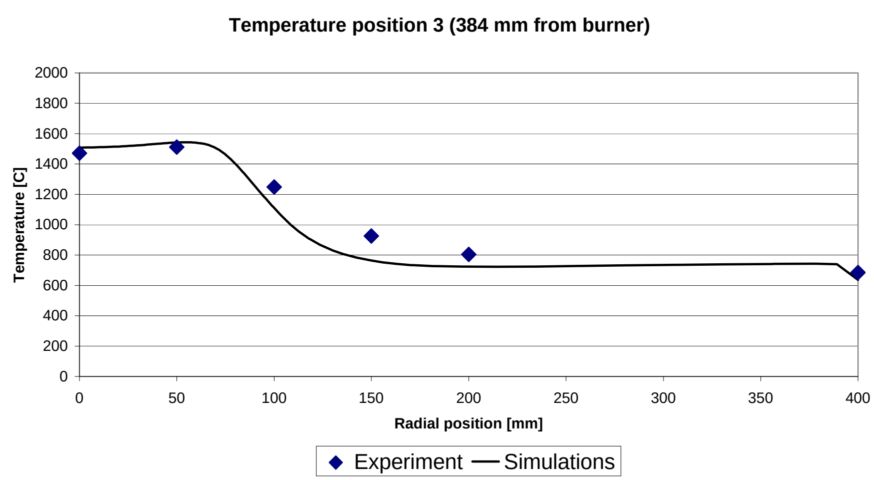
Validation case 80 kW propane flame

Air combustion



Temperature in °C

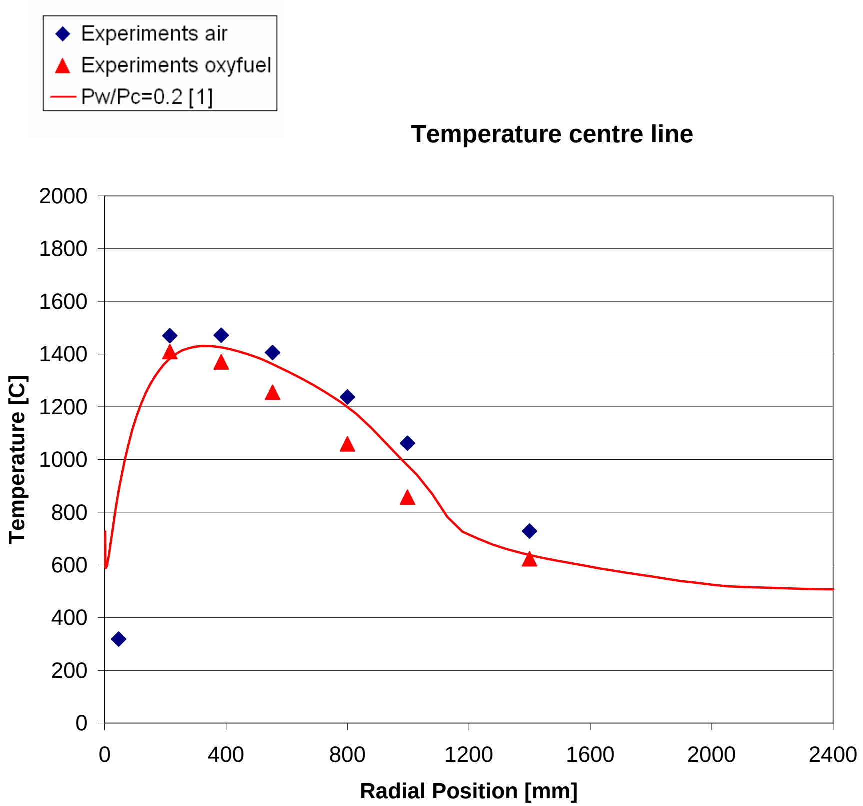




VATTENFALL

Validation case 80 kW propane flame

Oxyfuel combustion



Three submodels might be affected:

- Gas radiation
- Gas phase reactions
- Soot

[1] R Gupta; T Wall; University of Newcastle, Australia

VATTENFALL

Ongoing work

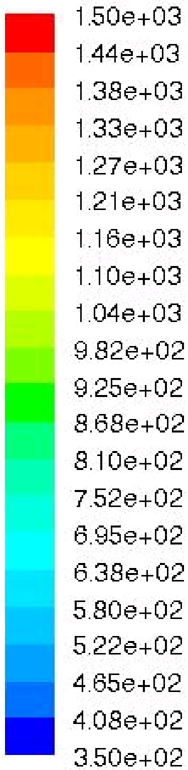
•Development of gas phase reaction schemes for oxyfuel conditions

•Measurement of soot in oxyfuel combustion and development of soot model

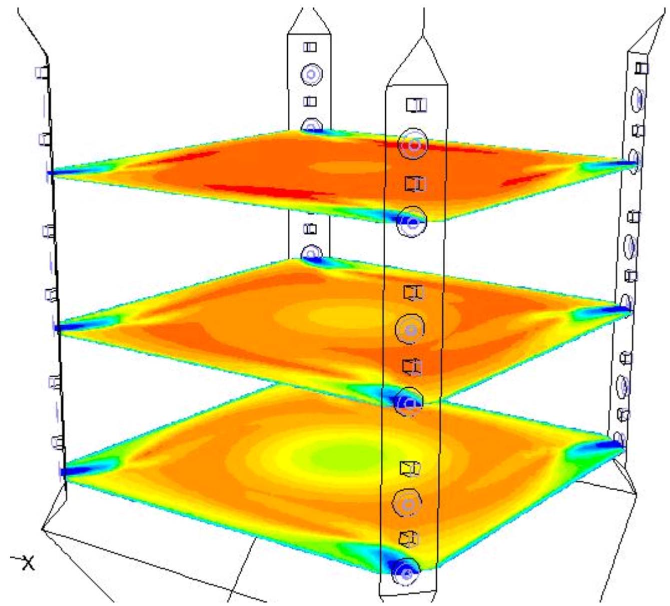
•Coal characterisation under oxyfuel conditions – including gasification reactions

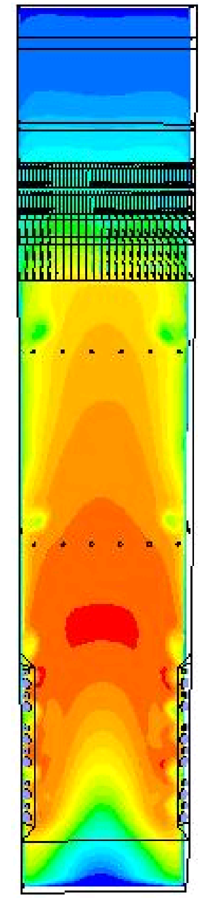
•Validation of models against laboratory coal flames

ENCAP: 1000 MW Alstom oxyfuel boiler



Temperature, scale in ºC.





Engineering calculations and CFD estimate similar global conditions for full scale applications, but what is reality?

VATTENFALL

Summary

• CFD is expected to be a useful tool in the development of the oxyfuel combustion technology.

• Development and validation of the submodels are necessary for oxyfuel conditions.

• Detailed measurement data from well defined flames in different scale are necessary as validation data.

• A lot of activities to develop and validate the CFD models for oxyfuel combustion conditions are ongoing!

Example: “OxyMod” - Development and Experimental validation of a Mathematical Modelling Methodology for Oxy-Fuel Combustion for CO2 Capture

Consortium including:
Vattenfall R & D AB, Universität Stuttgart (IVD), Chalmers University of Technology, National Technical University of Athens, Mitsui Babcock Energy Ltd, Fluent Europe Ltd
Financed by Reasearch Fund for Coal and Steel.

VATTENFALL

Ignition of oxy-fuel flames

TF Wall, S Khare, Z Farida, Y Liu

Cooperative Research Centre for Coal in Sustainable Development, Chemical Engineering,

The University of Newcastle, Callaghan, NSW 2308, Australia.

Email: Terry.Wall@newcastle.edu.au

2nd Workshop of the Oxy-fuel Combustion Network

25/26 January, 2007

Windsor, Conneticuct, USA

CCSD

Contents

CCSD

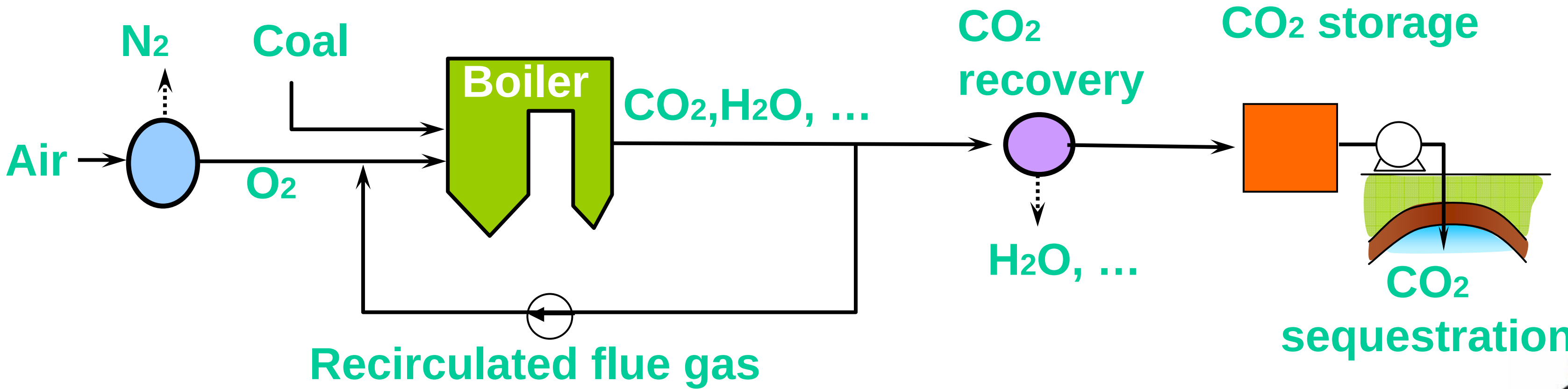
1. Introduction

Coal : **Most commonly used but high emitter of CO_2**

Therefore Reduction of CO_2 from PF power plant is called for …

Solution :

CO_2 recovery from PF power plant using Oxy-fuel technology



CCSD

Introduction: Ignition

Differences in ignition in O_2/CO_2 and O_2/N_2 environments have been observed for

….. Coal particles

….. Particle clouds, and

….. Flames

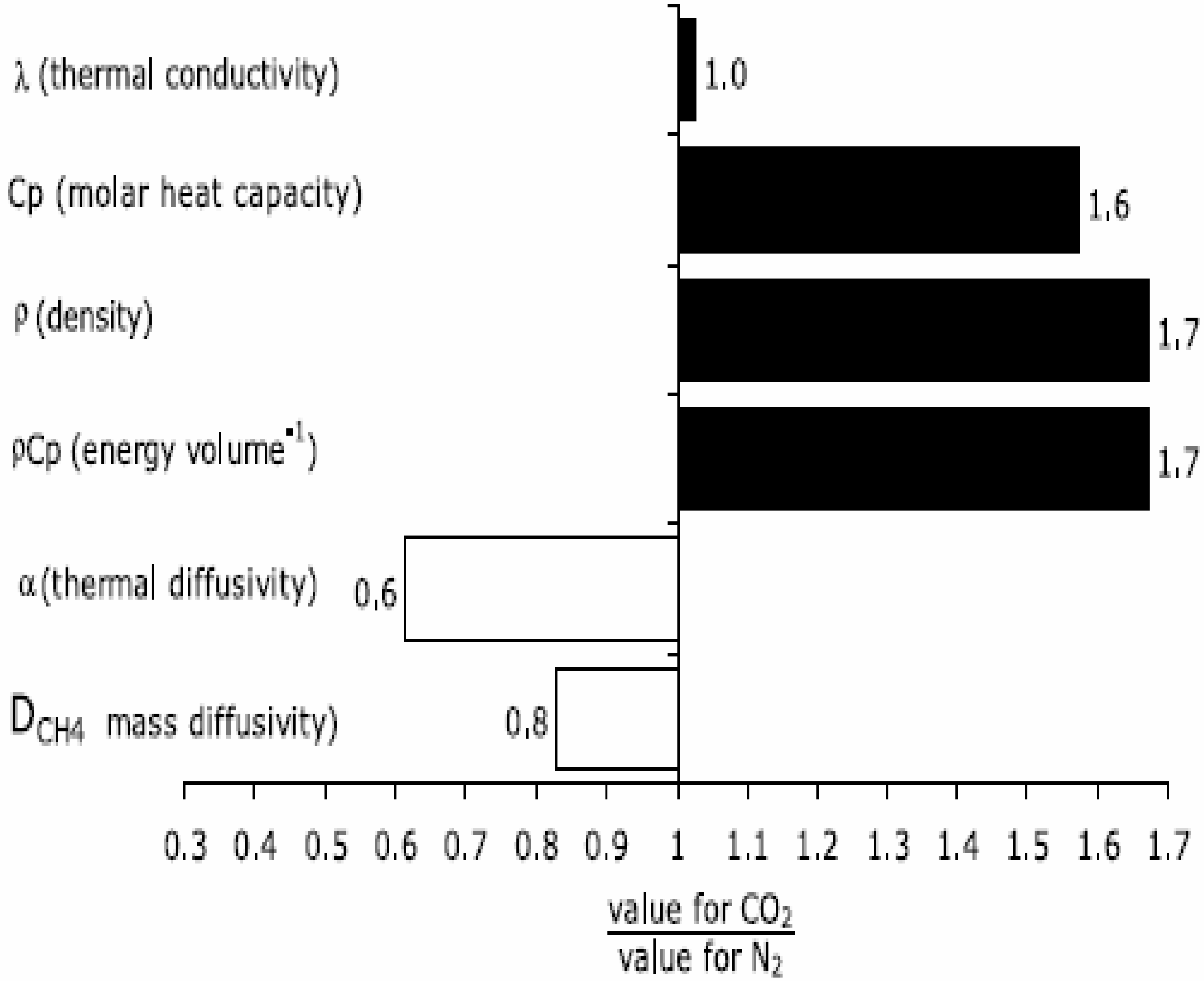
The paper examines the mechanisms for flame ignition differences, in terms of

….. Differing gas flows through the burner and resulting flame aerodynamics

….. Differing gas properties,

CCSD

Property / ratio



Impact for air to oxyfuel retrofit

- Higher O_2 thru burner
- Lower burner velocity, higher coal residence time in furnace
- Slower flame propagation velocity

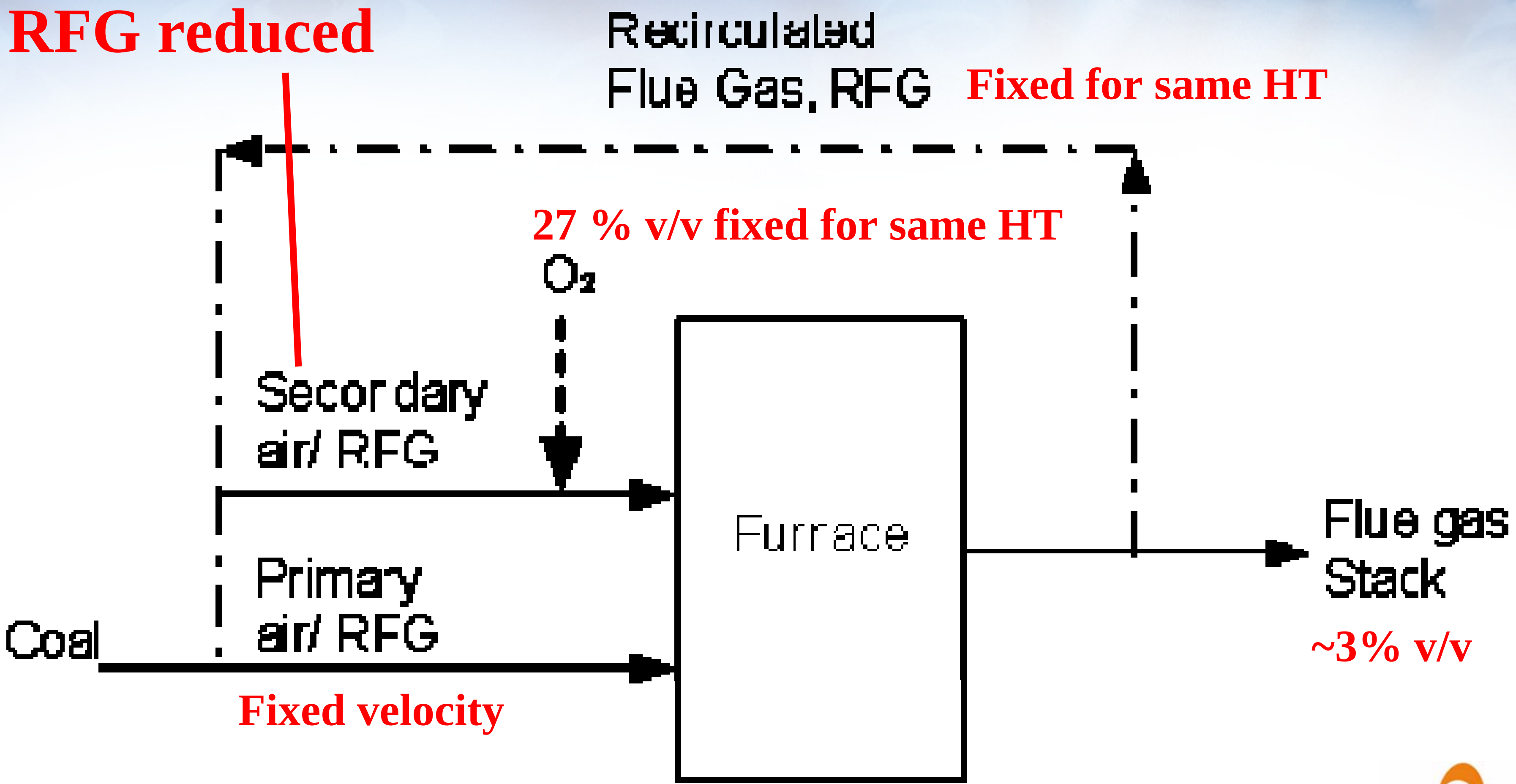
Gas property ratios for CO2 and N2 at 1200 K

Properties from Shaddix, 2006

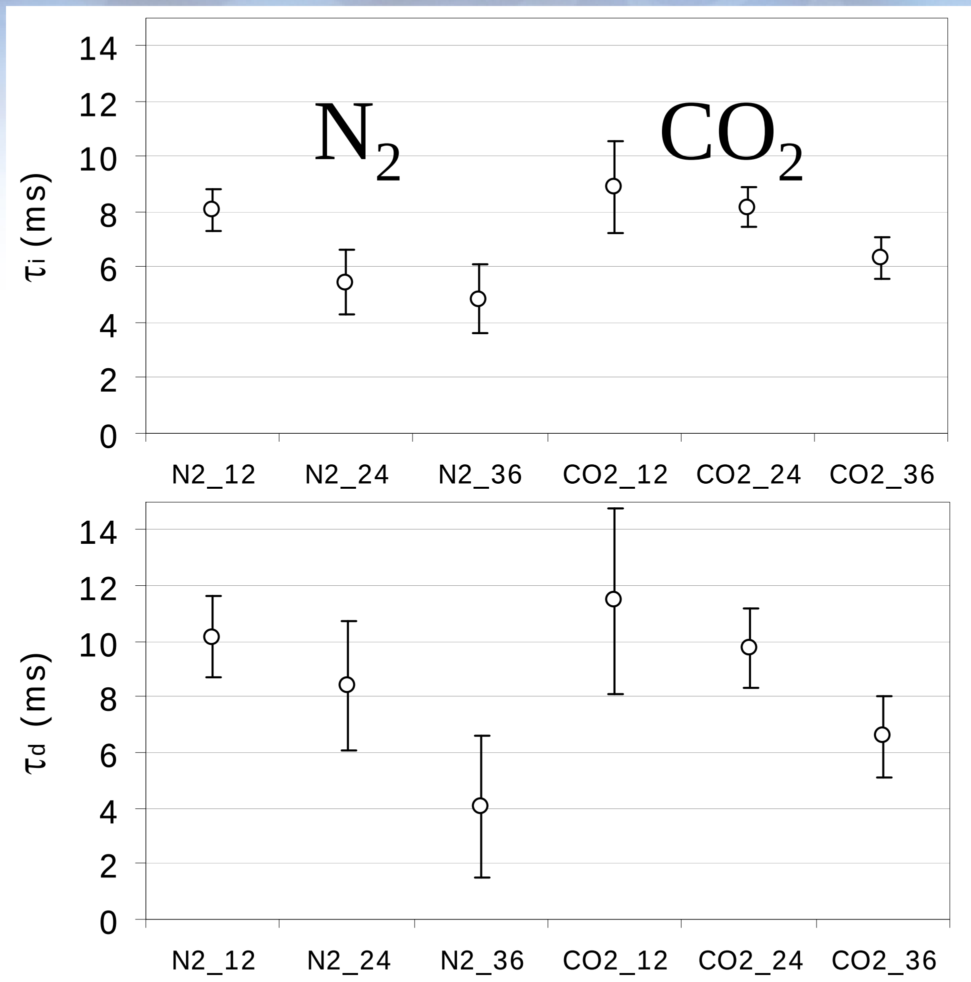
CCSD

Burner flow comparisons for a retrofit

Therefore secondary RFG reduced



Ignition and Devolatilization Times: Pittsburgh Coal



"CO2 affects (particle) ignition because of its high rho.Cp and affects devolatilization flame because of decreased diffusion of fuel vapor"

Shaddix, Clearwater Coal Conference, 2006

CCSD

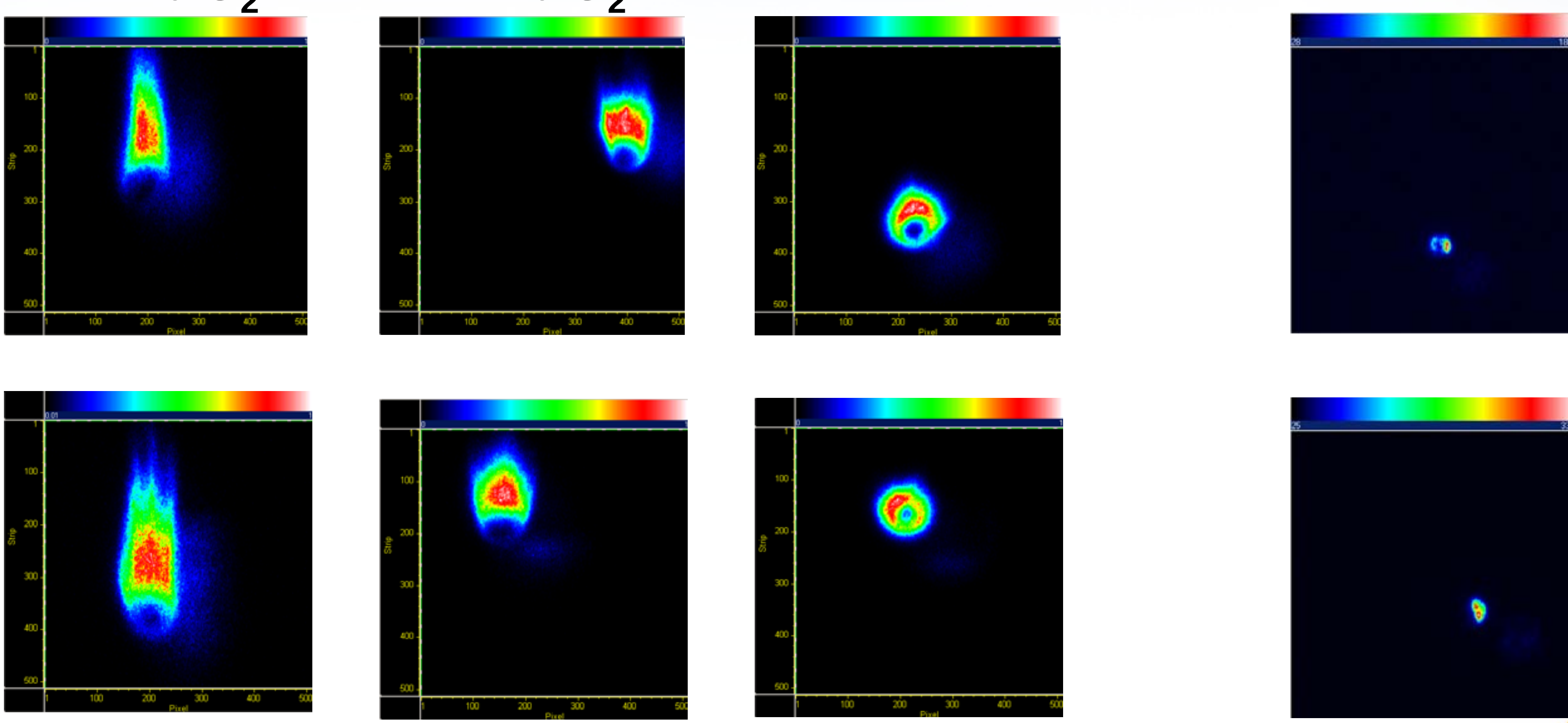
PARTICLE IGNITION: Effect of O_2 and N_2/CO_2 on Devolatilization

Pittsburgh Coal | **Black Thunder Coal**

$12\%\ O_2$ | $24\%\ O_2$ | $36\%\ O_2$

N_2

CO_2



< ~2mm >

Shaddix, Clearwater Coal Conference, 2006

CCSD

CLOUD IGNITION

Okazaki and coworkers, in experiments on pf clouds in a spherical chamber (bomb) found that flame propagation velocities were 1/3~1/5 in oxyfuel compared to air

Explained in terms of low thermal diffusivity for oxyfuel:

$$\text{Alpha} = k / \text{rho.Cp}$$

CCSD

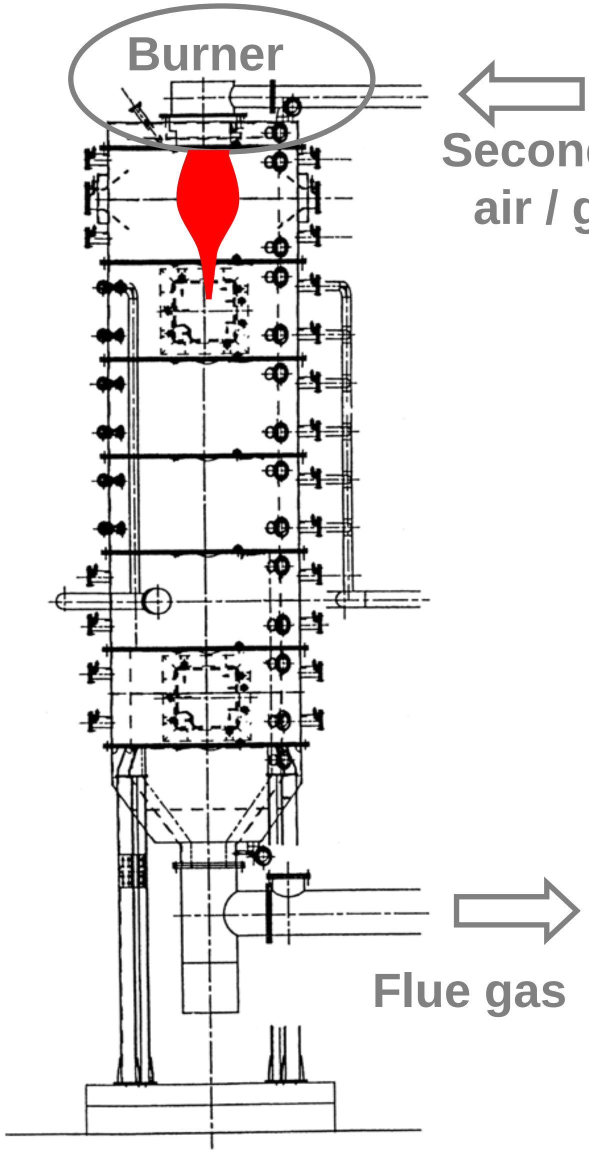
2. Objective

- Examines Flames from
  - A pilot-scale study of ~0.8 – 0.48 MWt flames, for which experimental data is available
  - comparing using FLUENT

- Fired with both **Air** and as **Oxyfuel**

CCSD

3. Experimental: Pilot scale furnace



Furnace output:	1.2 MWt
Furnace size :	ID – 1.3 m
	L – 7 m
Burner :	Swirl burner
	Small burner quarl
Tests:	Air & Oxy-firing

CCSD

Test Conditions

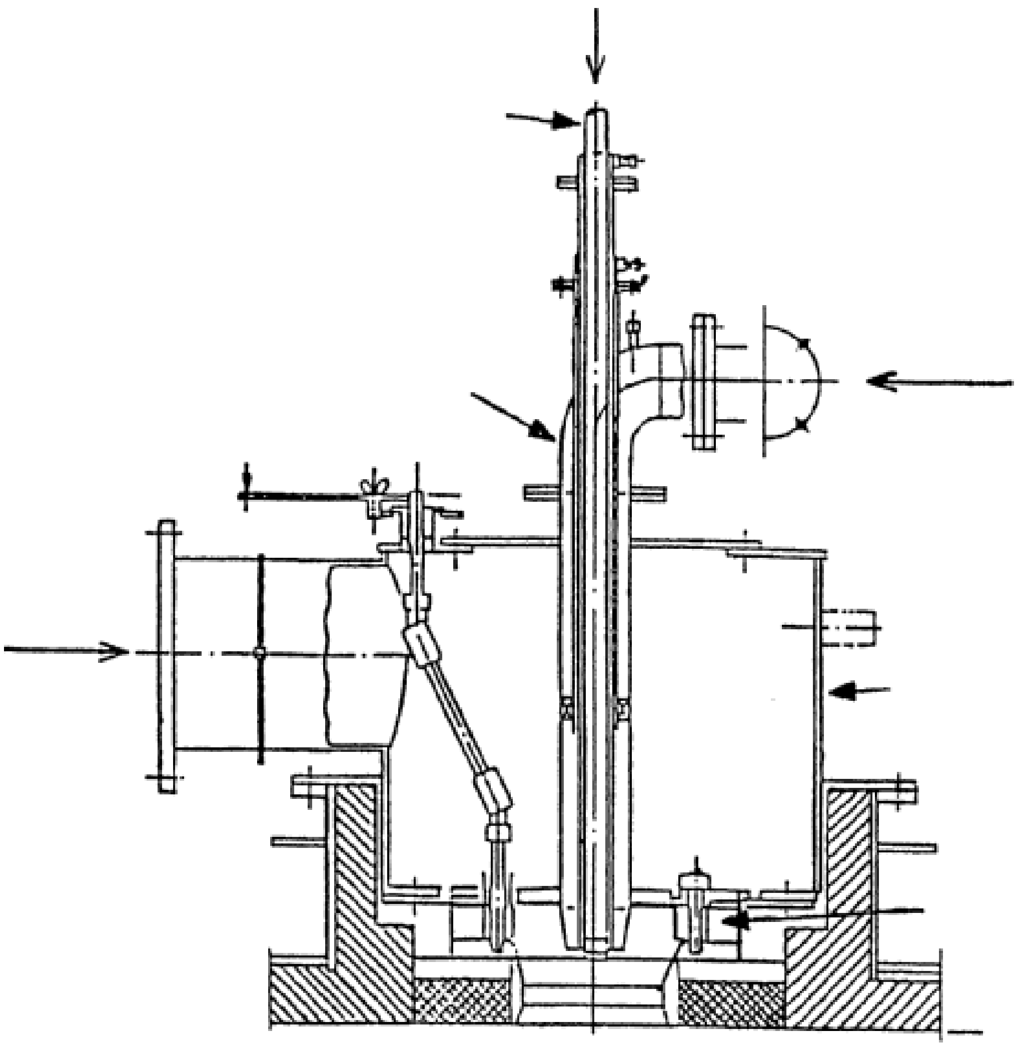
Combustion Case		Air-case	Oxy-case
Heat Input	MW	0.8 – 0.48	
Flue gas O_2 at AH inlet	Dry %	3.5 – 4.3	
Total O_2 at burner inlet	Wet %, calc	21	**27**

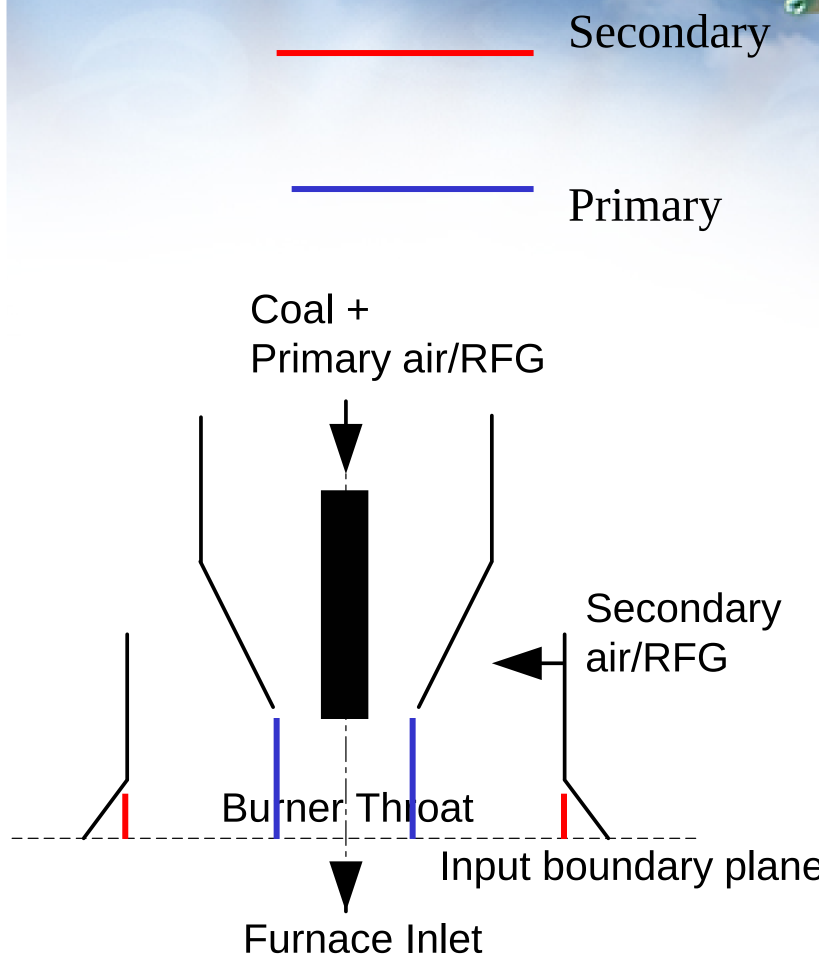
Coal analysis

	Coal-A
Heating Value (MJ/kg)	23.7
Proximate Analysis (% dry)	
M	8.8
A	19.3
VM	25.7
FC	55.0
Ultimate Analysis (% dry)	
C	63.5
H	2.83
N	0.73
O	13.49
S	0.15

CCSD

Burner and model boundary conditions





CCSD

Test Conditions continued …

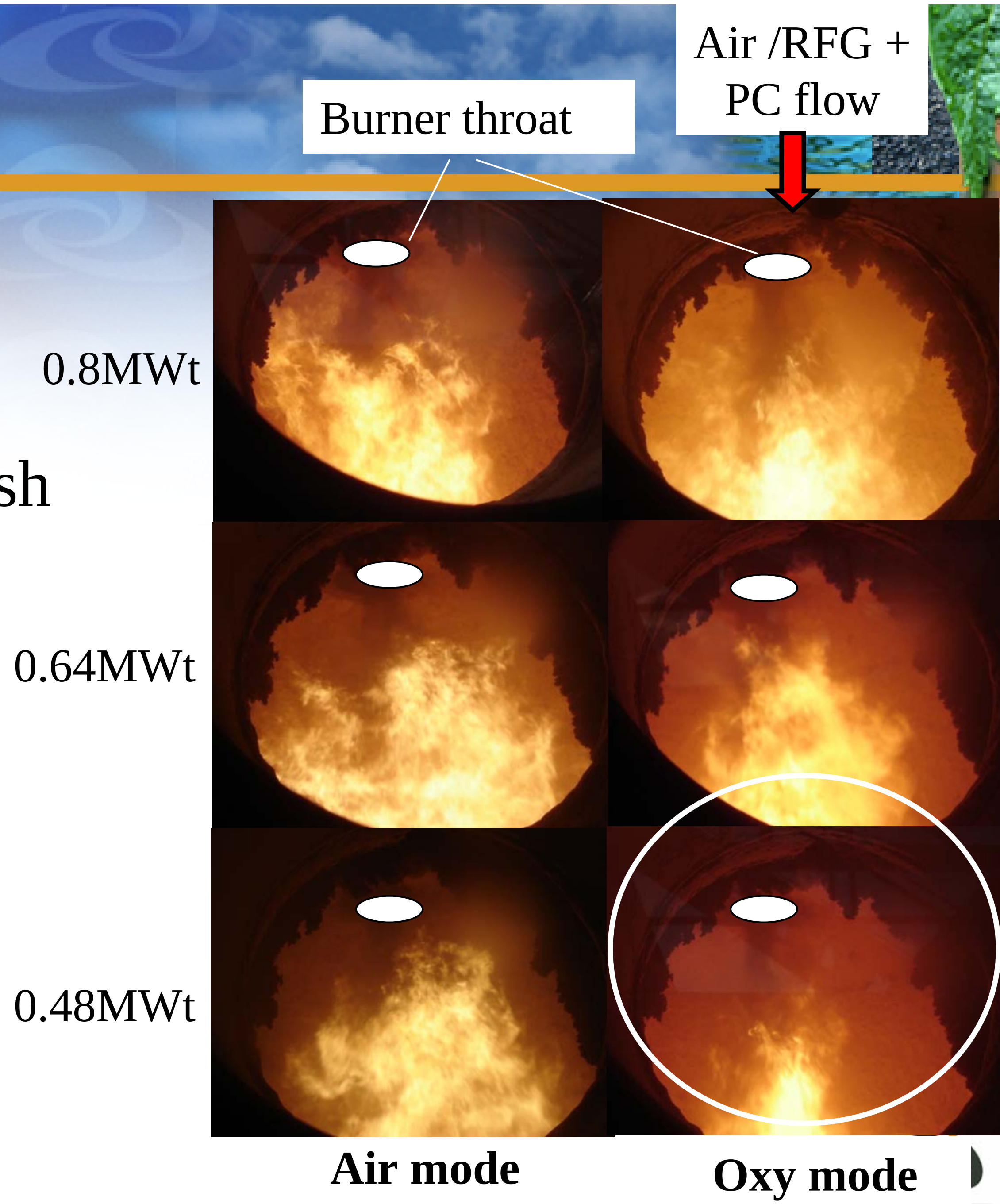
Parameter	Coal-A	Full load		Partial load	
		Air-Case	Oxy-Case	Air-Case	Oxy-Case
Coal flow rate	kg/hr	120	120	72	72
Pri velocity	m/s	20	23	17	21
Sec velocity	m/s	35	21	18	12
Sec swirl number	-	0.2	0.2	0.2	0.2
Pri momentum flux	$kg/s.m^2/s^2$	35.7	54.1	20.9	36.8
Sec momentum flux	$kg/s.m^2/s^2$	270.2	74.1	38.2	16.4
Momentum Ratio (Pri/Sec)	-	**0.13**	**0.73**	**0.55**	**2.25**

Preheated air: primary 350K and secondary 550 K, Wall conditions 1200 K

CCSD

Flame shape & Ignition delay

- All Type-0 flames
- Difficult to distinguish between combustion modes using stills



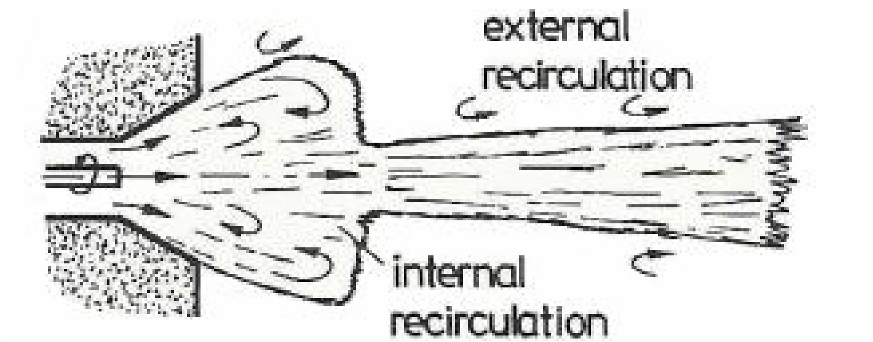
CCSD

IFRF flame types from swirl burners

Type-0

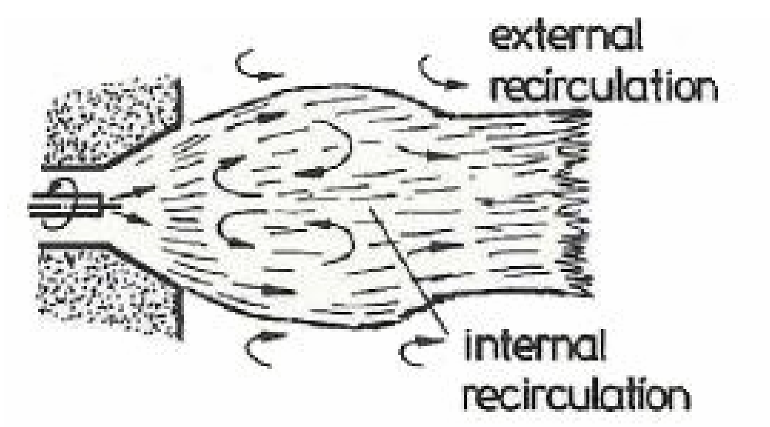
Lo S

Type-1



Hi S (S>0.6) ,
Lo v_2

Type-2

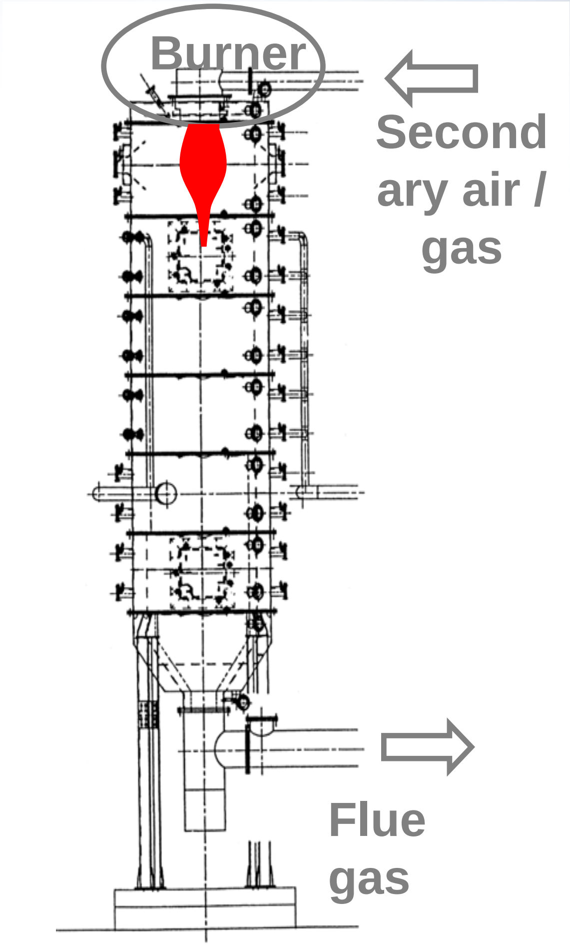


Hi S, Hi v_2

CCSD

4. Theoretical Modeling

- Modeling using '**GAMBIT**' and '**FLUENT**-6.2' Software
- Simulating domain: Furnace chamber
- Model: 2-D Axisymmetric swirl
- Meshing scheme (finer near burner zone)
- Grids of 10000, 32000, 46000, 50000 cells are tested
- **Air** and **Oxy** combustion



Models selected

- Continuity equation
- Momentums (axial -radial -tangential velocity) components
- Turbulence: k - ε model
- Energy equation
- Radiation: P1 (tentatively)
- Gas-phase reaction and Disperse phase
- Coal Devolatilization: single reaction model
- Char burnout: kinetics/diffusion model

} *Data from the* ***DTF*** *experiments*

DTF*: Drop Tube Furnace*

CCSD

Analysis of

- Temperature field and ignition location
- Velocity field & flow pattern
- Comparison of measured and predicted temperature
- Burn-out, residence time, heat transfer, species concentrations

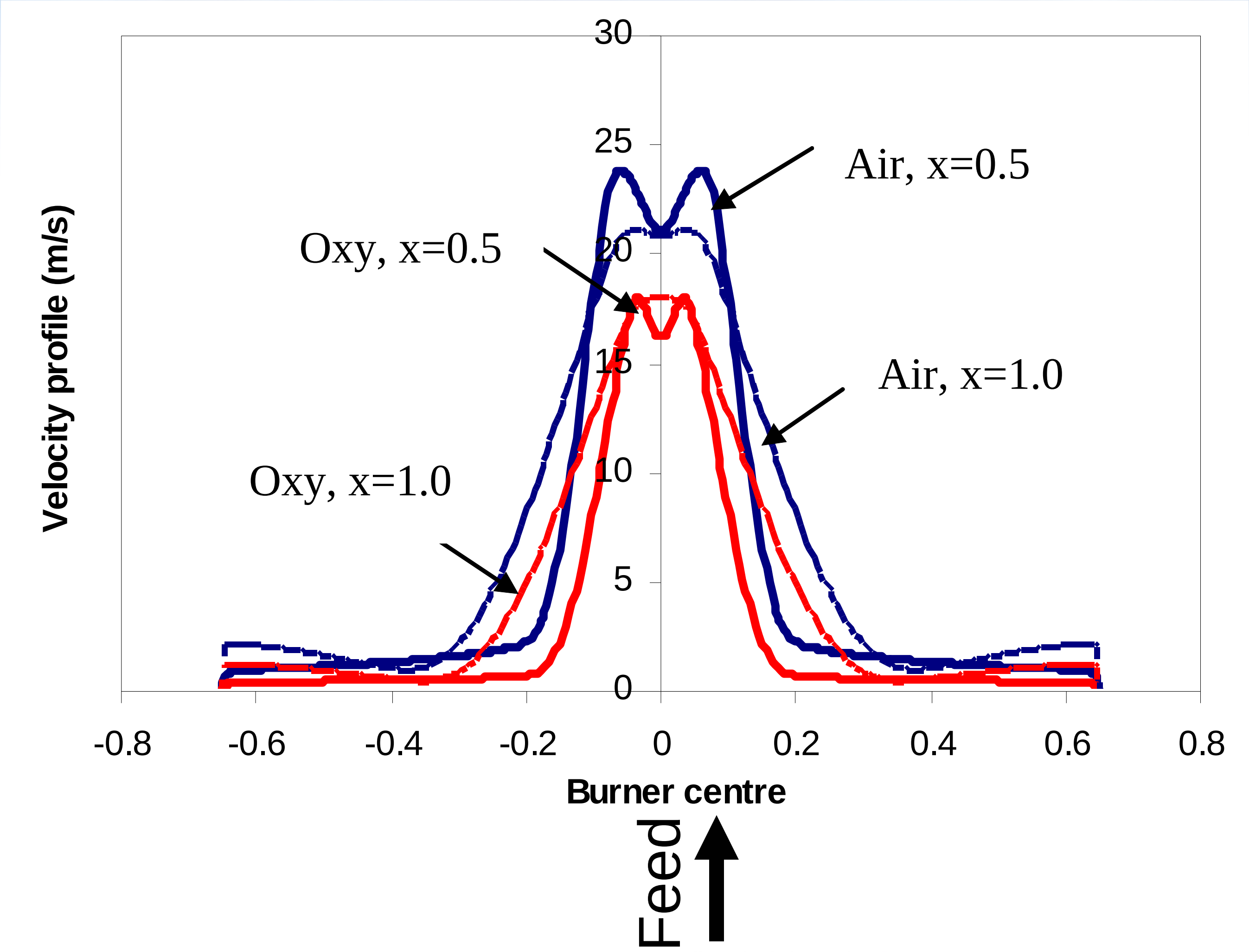
Sensitivity Study on

- Load (full and partial)
- Swirl Number

CCSD

5. Results & Analysis

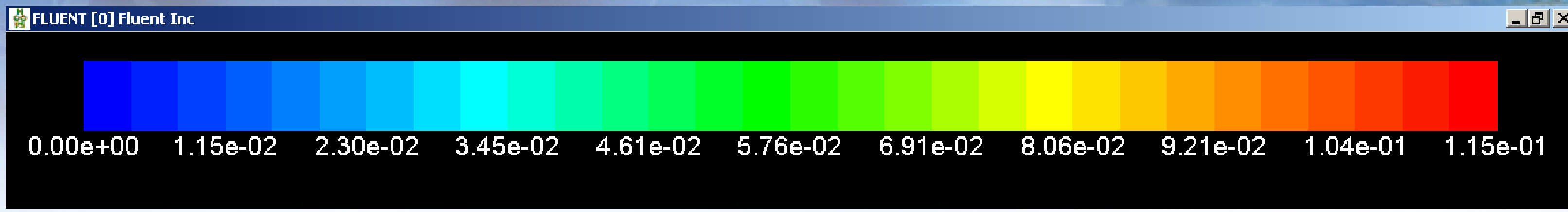
Flow velocity



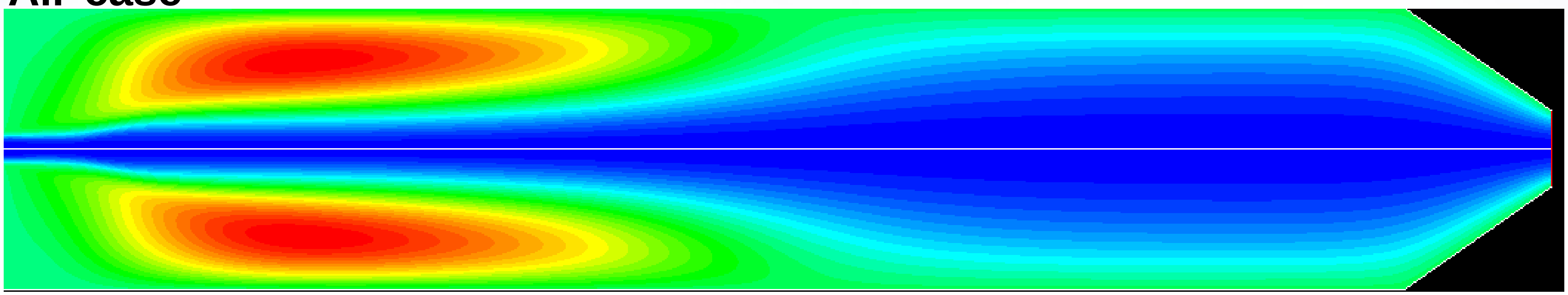
CCSD

Flow Contours

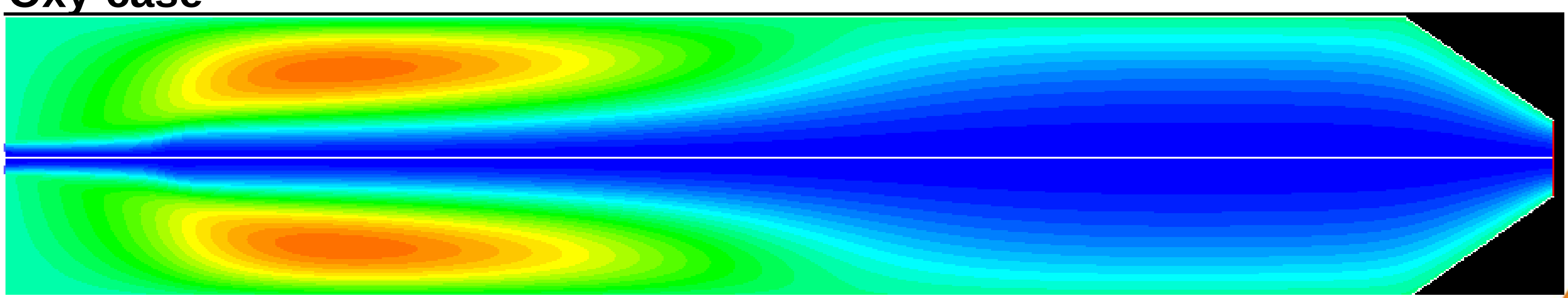
Oxy-case



Air-case

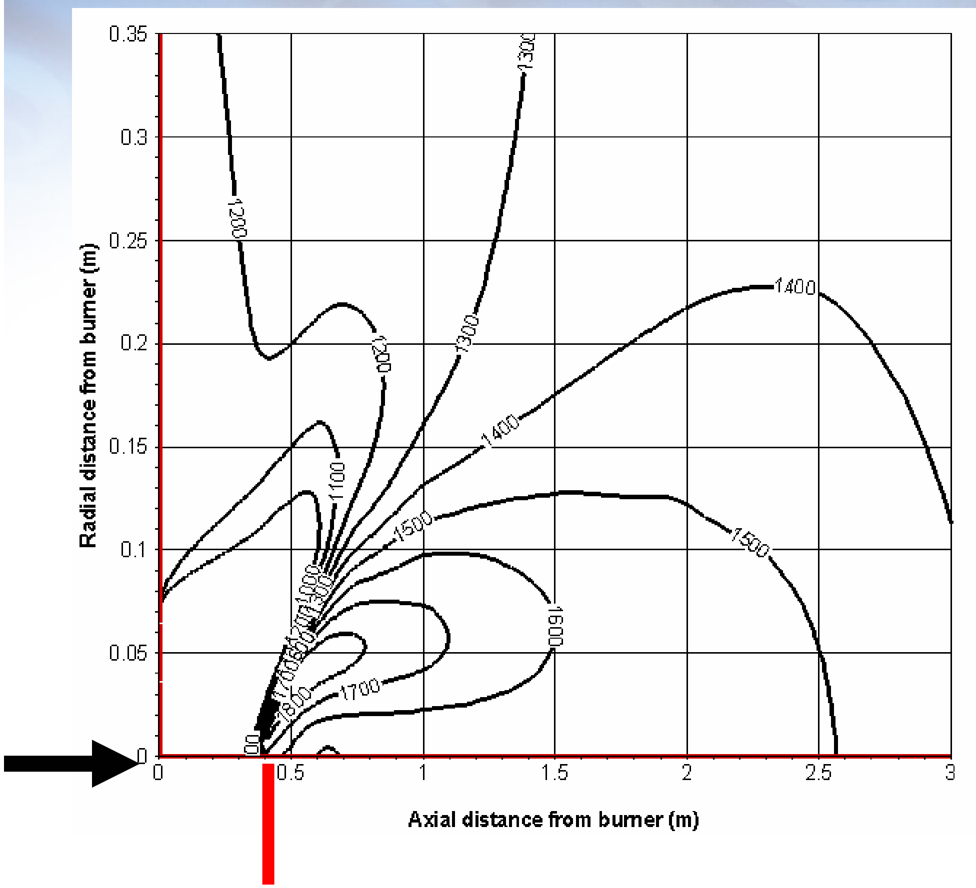


Oxy-case

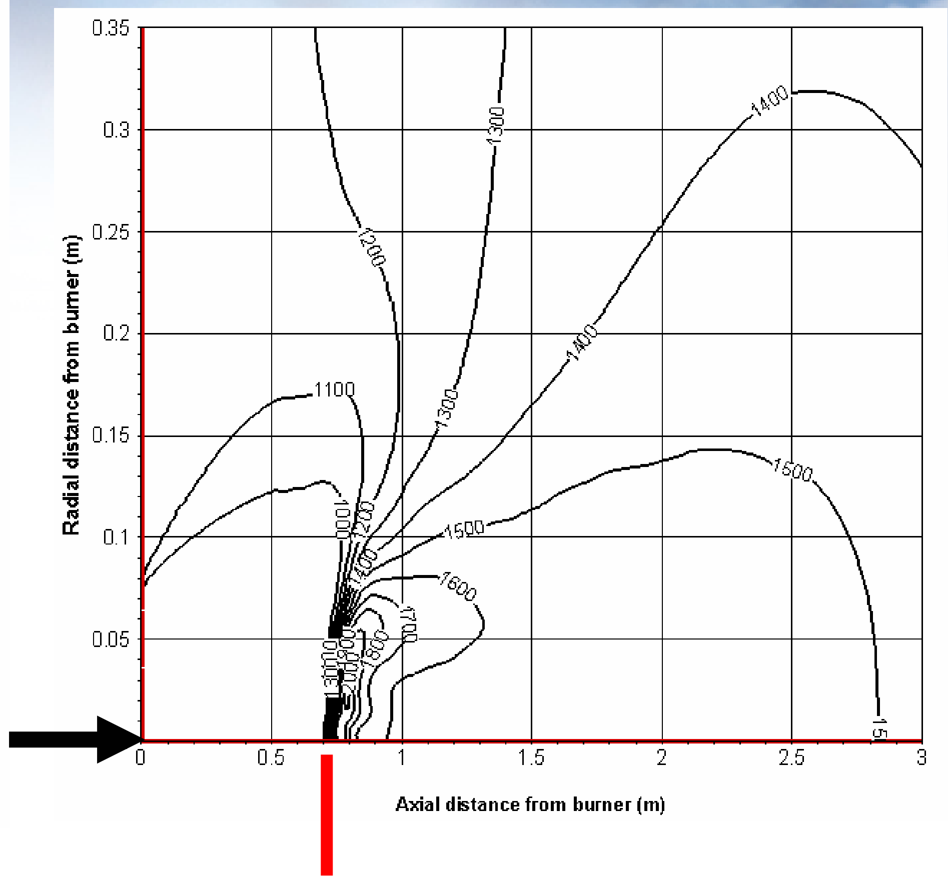


Gas Temperature Contours

Air-case



Oxy-case

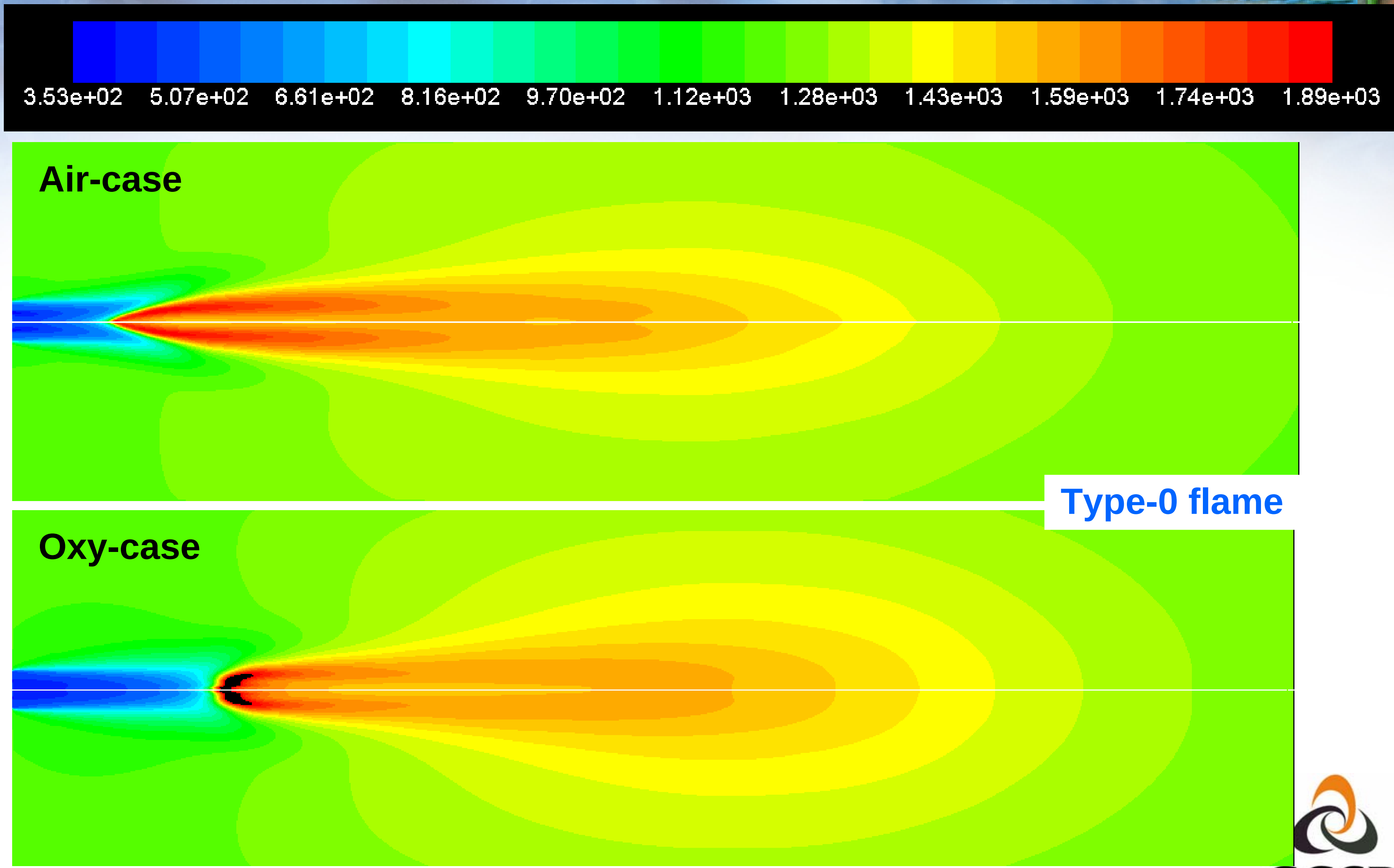


Ignition

Ignition

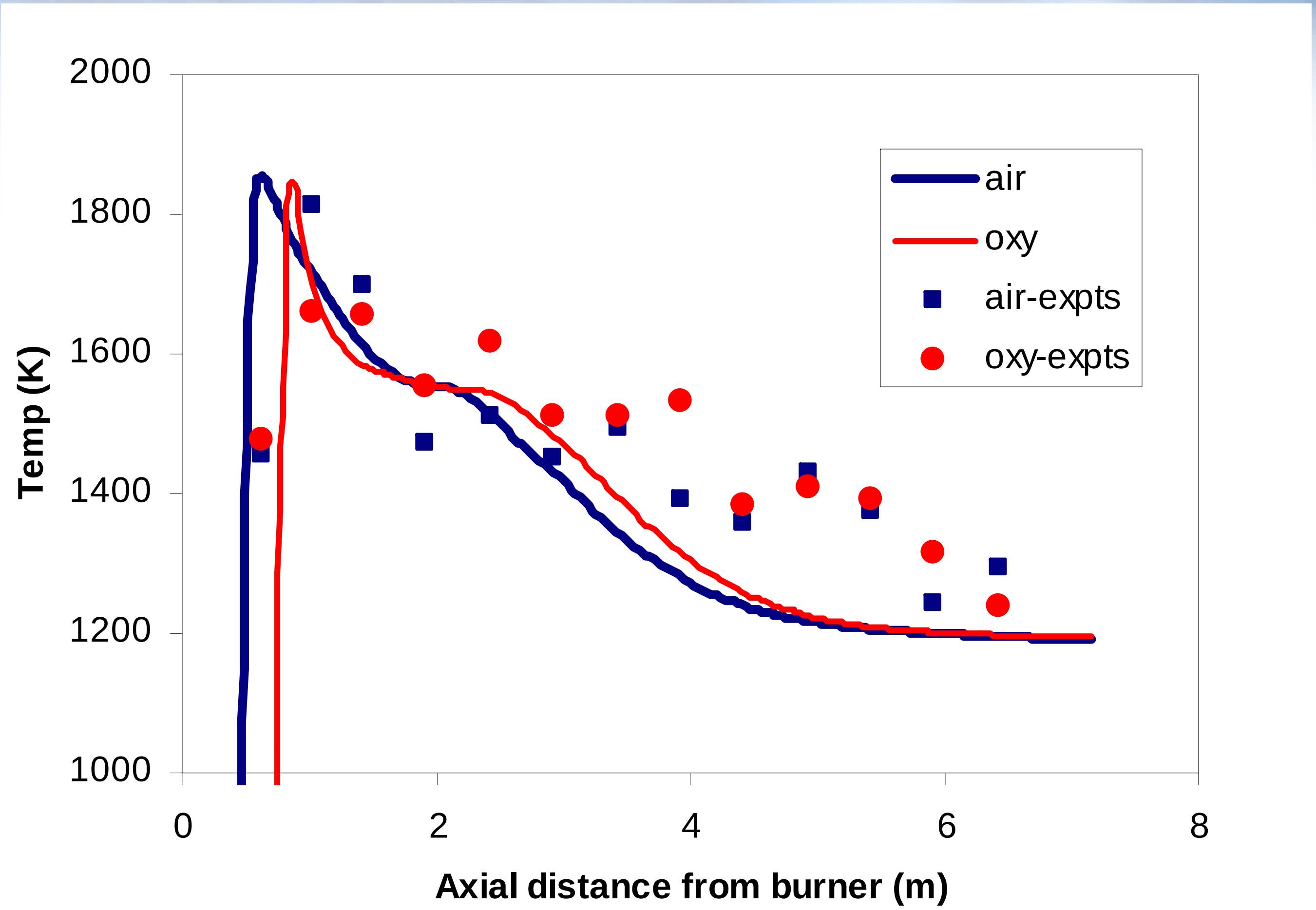
CCSD

Gas Temperature Contours

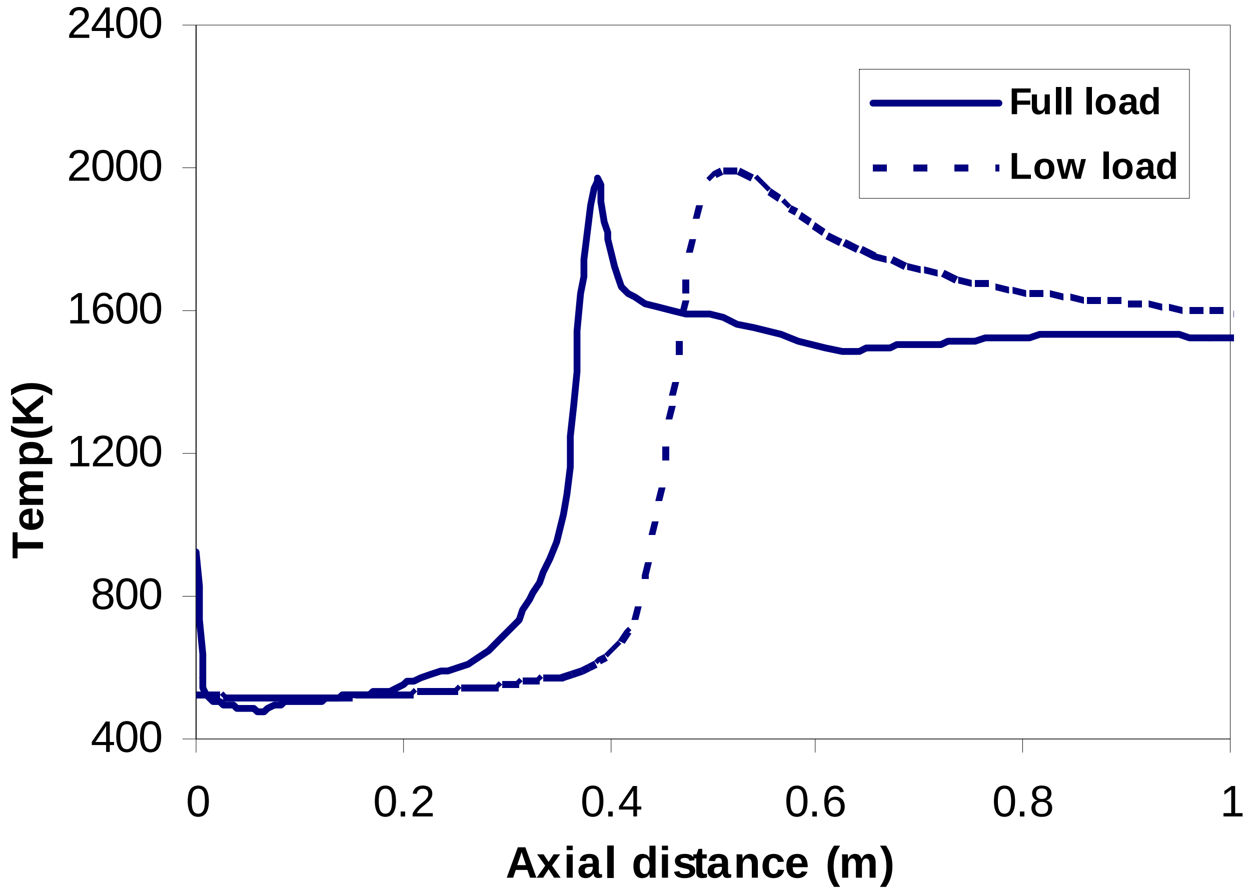


Gas Temperature profile: Air and Oxy

Full load

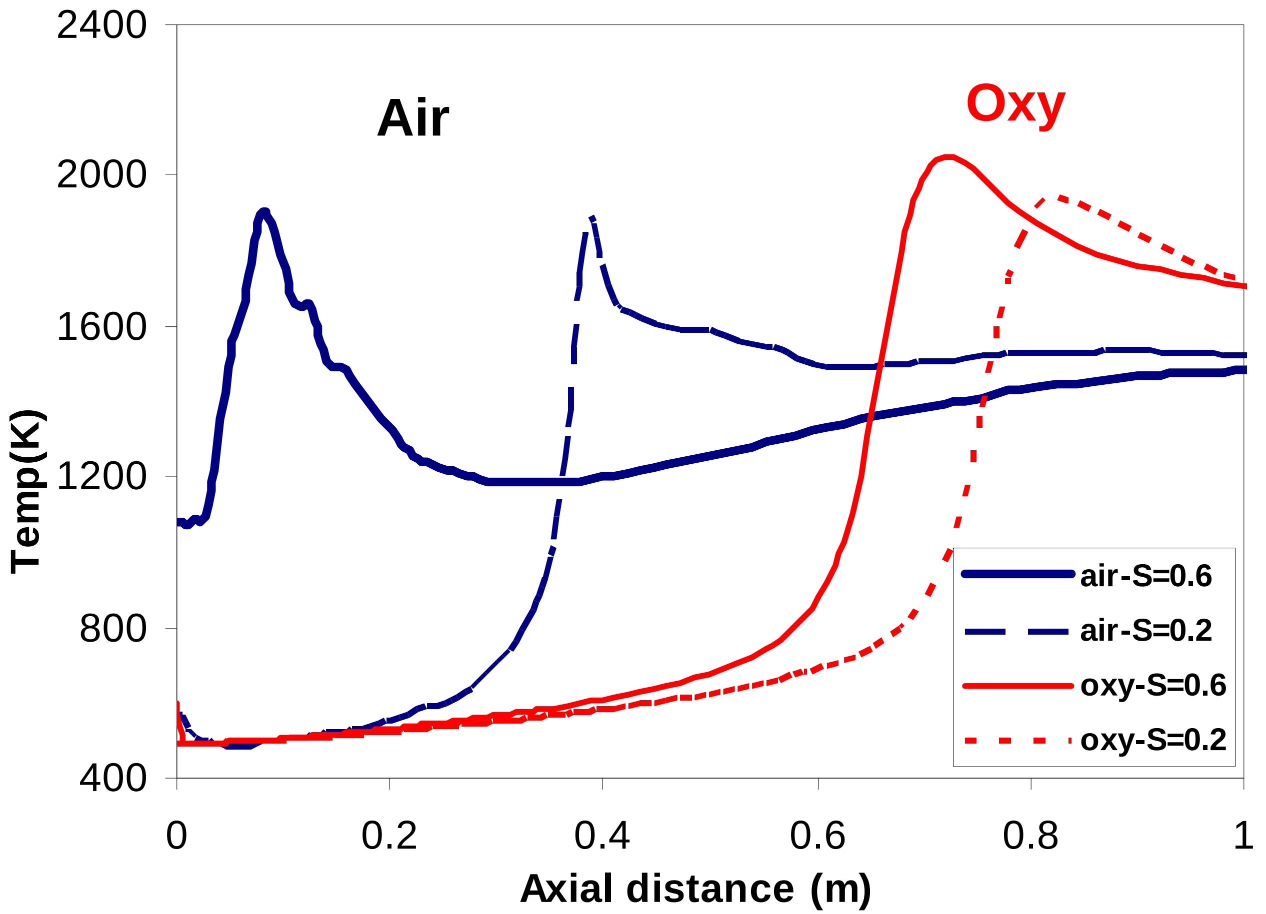


Sensitivity Analysis
Effect of full and partial load: Air-case



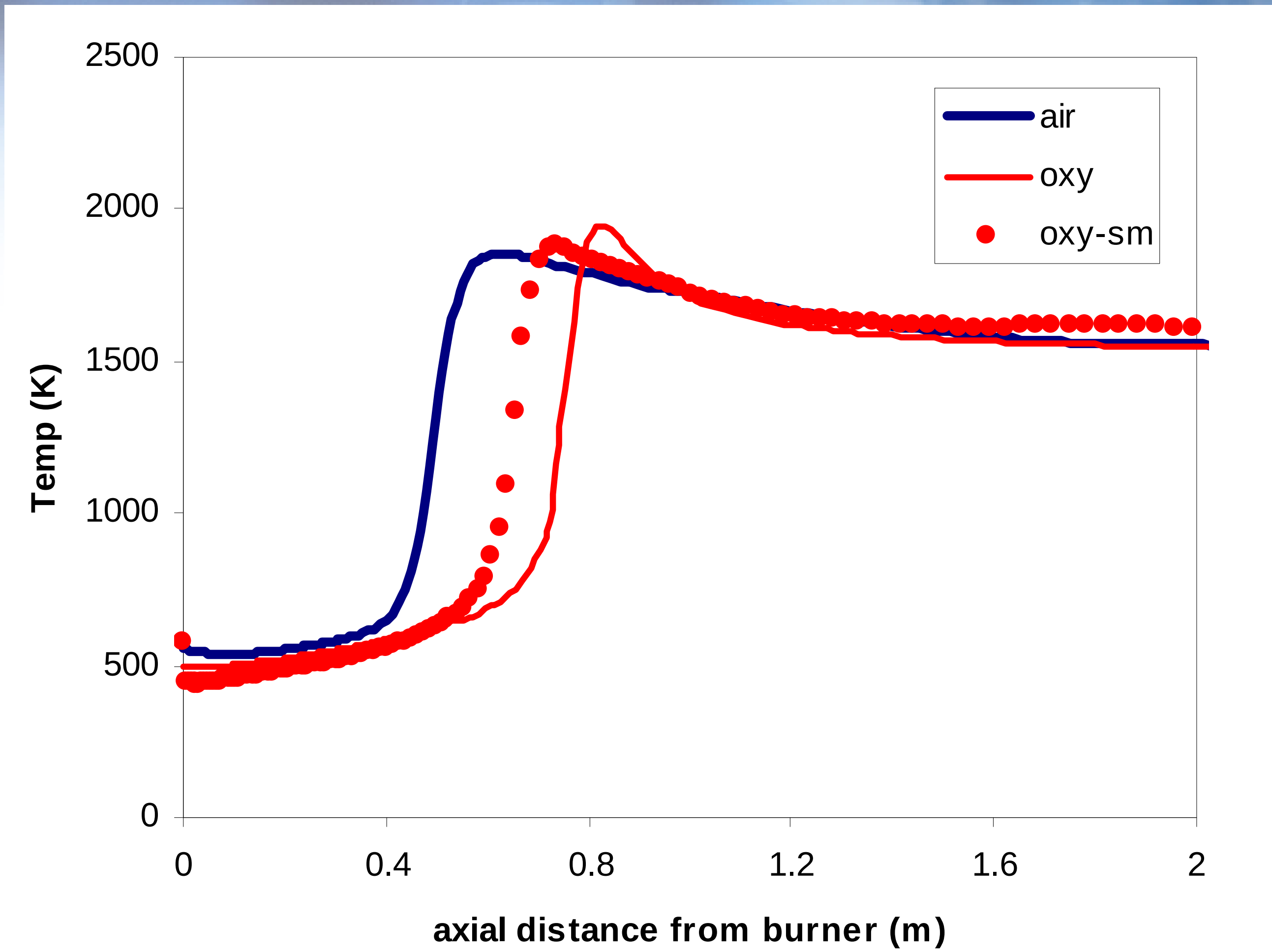
CCSD

Effect of Secondary Swirl Number, Primary is Unswirled



CCSD

Effect of momentum flux



✓ Confirms the significance of **momentum flux** and **Gas properties** on flame ignition

6. Conclusions

✓ CFD predictions have indicated differences in:

- **Flame ignition location in air & oxy**
- **Burner jet flows**

✓ Study confirms significance of flame ignition location due to:

- **Momentum flux**
- **Gas properties**

CCSD

- ✓ Flame **Type-0** is observed for all flames

" Practical air-flames are Type-2, the possibility exists for:

Type-2 (air) → Type-0 (oxy)

- ✓ Burnout, species profiles, residence time and heat transfer are all well predicted

7. Future Work

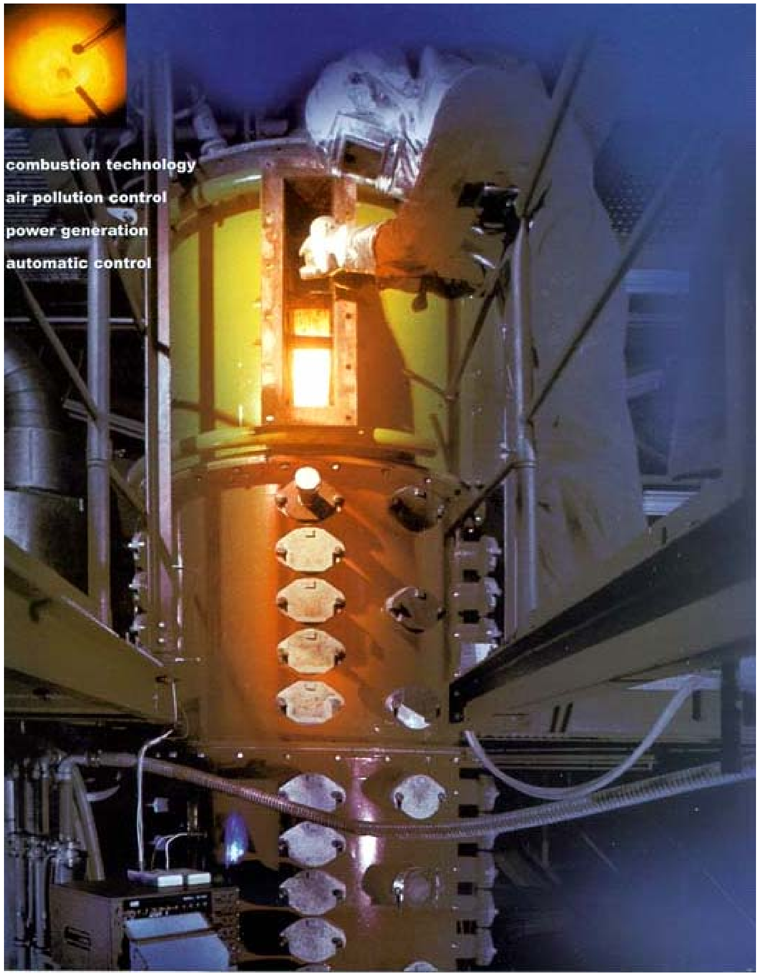
- Development of 3-D model for large scale furnace
- New radiation coefficients testing
- Further validation, sensitivity testing needed

Thank you!

Institut für Verfahrenstechnik und Dampfkesselwesen
Institute of Process Engineering and Power Plant Technology
Prof. Dr. techn. G. Scheffknecht

Universität Stuttgart

R&D Oxy-fuel Topics
at IVD
University Stuttgart



Joerg Maier

maier@ivd.uni-stuttgart.de

Organization of IVD

Universität Stuttgart

Prof. Dr.-techn. G. Scheffknecht
Director

Prof. Dr.-Ing. Helmut Seifert
Forschungszentrum Karlsruhe GmbH

Institute of Techn. Chemistry
Thermal Treatment of Waste

Departments

- **Dipl.-Ing. J. Maier** – Combustion Systems and Steam Boilers
- **Prof. Dr.-Ing. G. Baumbach** – Air Pollution Prevention
- **Dipl.-Ing. H. Thorwarth** – Fuels and Measurement Techniques
- **Dr.-Ing. R. Berger** – Decentralized Energy Conversion
- **Prof. Dr.-Ing. PD U. Schnell** – Combustion and Steam Boiler Simulation
- **Dipl.-Ing. T. Weißbach** – Power Generation and Automatic Control

Actual R&D Topics

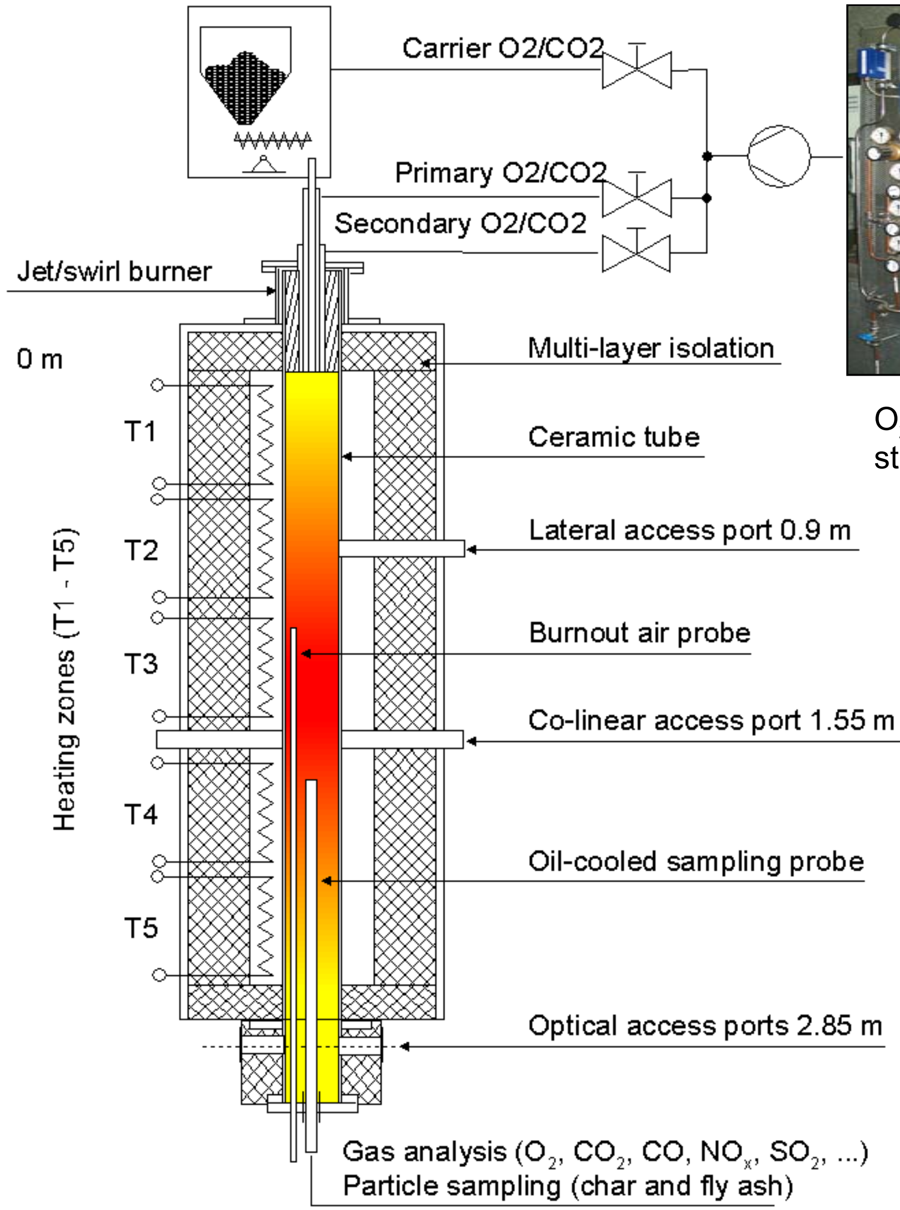
Universität Stuttgart

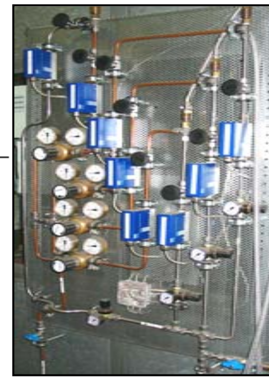
- Fuel characterization (electrical heated pf reactors)
  - Combustion
    - Rank of coal (bituminous, lignite…)
    - Emission formation, recirculation (NO_X, CO, SO_2…
    - Char burnout and fly ash formation
  - Pyrolysis under CO_2 and N_2 atmosphere
    - Volatile release and char formation/reactivity
    - Tar measurements
- Technical scale combustion tests ($0.5MW_{th}$)
  - Combustion and emission behavior, slagging, fouling, corrosion
  - Component development and test (burner…)
  - Plant handling and operation, safety requirements
- Model development and combustion simulation (AIOLOS)

Fuel characterisation combustion (20kW)

Boundary combustion test conditons

Universität Stuttgart





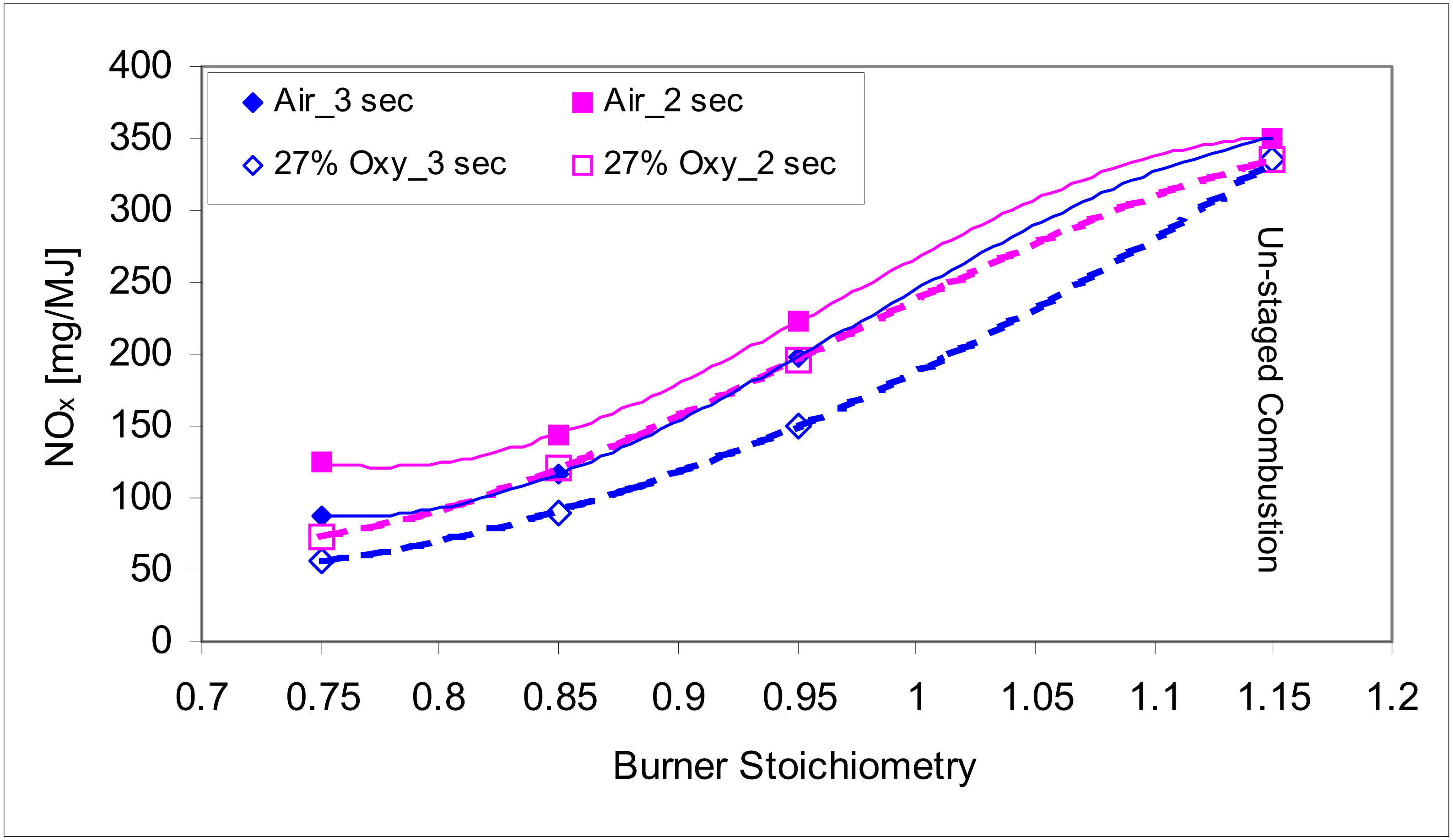
O_2/CO_2 mixing station

O_2/CO_2 supply tanks

Experiment Conditions	Air & 27% O_2/73% CO_2
Coals	Klein Kopje and Lausitz
Oxidant flow through burner	Constant for all cases [6.7 m³/h]
$\lambda_{overall}$	1.15
λ_1 (burner stoichiometry)	0.75, 0.85, 0.95
T_1	1, 2 and 3 seconds

NO_x Emission- Klein Kopje Coal

Universität Stuttgart

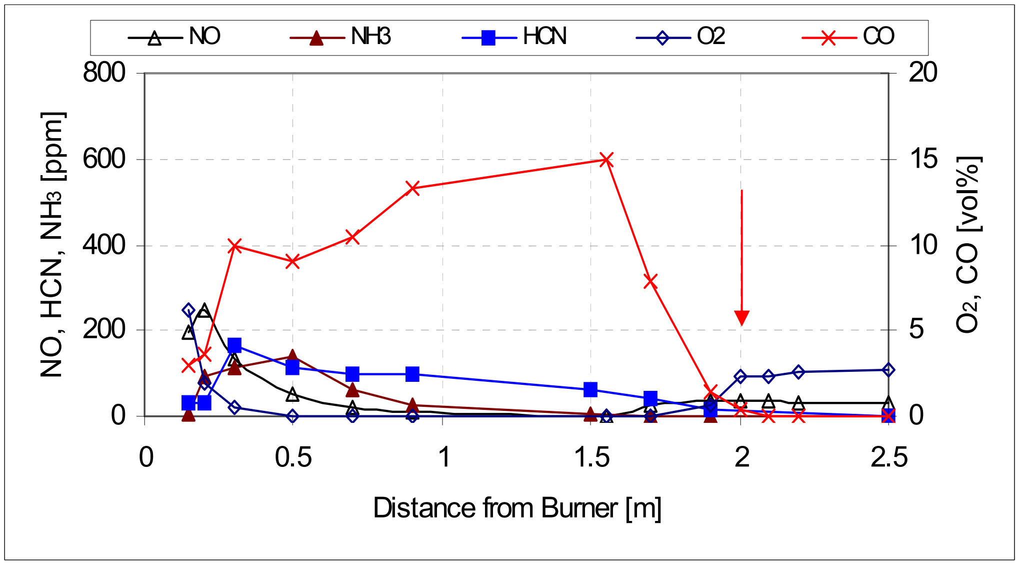


➢Primary NO_x reduction method is applicable for Oxy-Coal Combustion

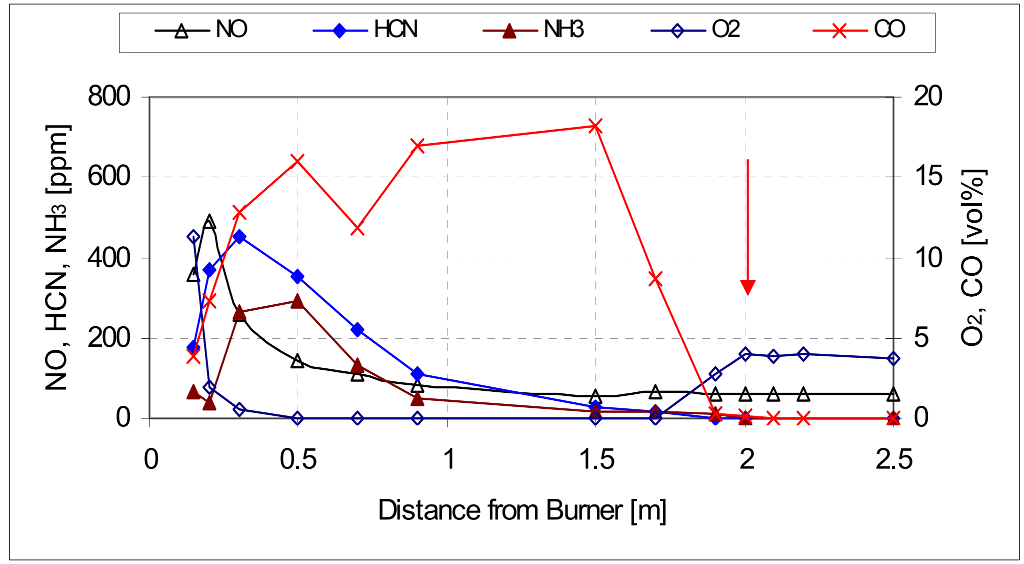
NO_x – Formation - Lausitz Coal

Universität Stuttgart

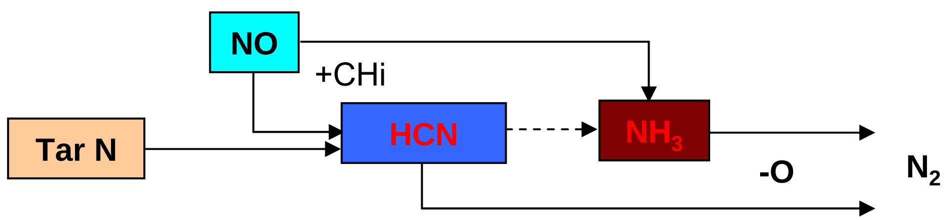
Air Combustion



Oxy-Coal Combustion (27% O_2)



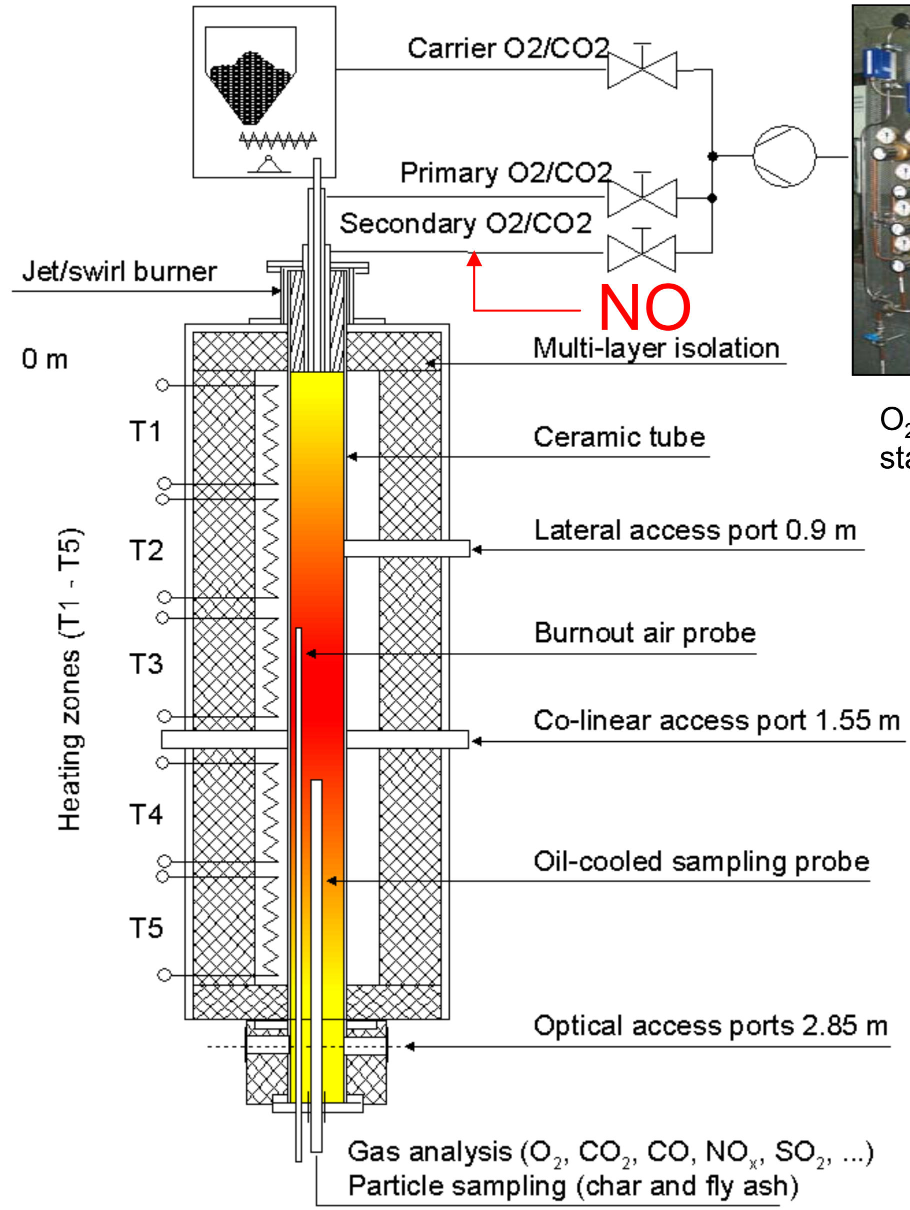
Overall Stoichiometry = 1.15, Burner Stoichiometry = 0.75, Residence time in reduction zone ~ 3 seconds

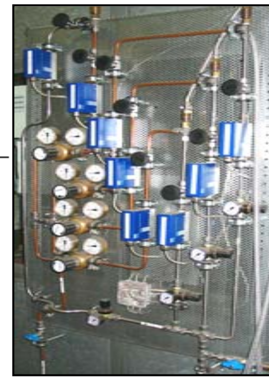


Precursors of NO_x, both HCN & NH_3, : Amino side chain produces NH_3

Impact of recirculated NO

Universität Stuttgart





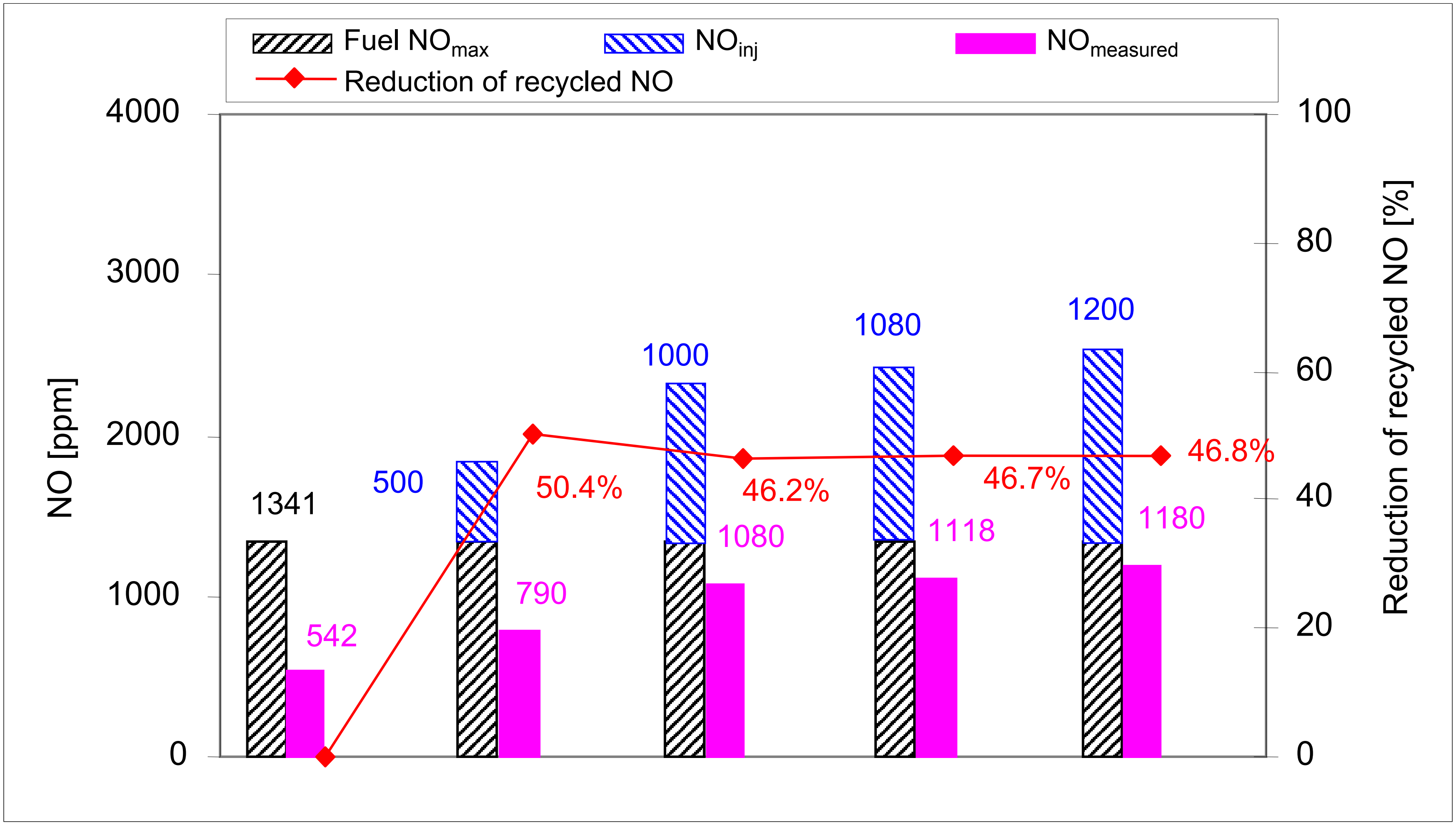
O_2/CO_2 mixing station

O_2/CO_2 supply tanks

Experiment Conditions	Air & 27% O_2/73% CO_2
Coals	Klein Kopje, Lausitz
Oxidant flow through burner	Constant for all cases [6.7 m³/h]
$\lambda_{overall}$	1.15
λ_1 (burner stoichiometry)	0.75, 0.85, 0.95
T_1	1, 2 and 3 seconds

Un-staged Combustion (Lausitz Oxy-Coal)

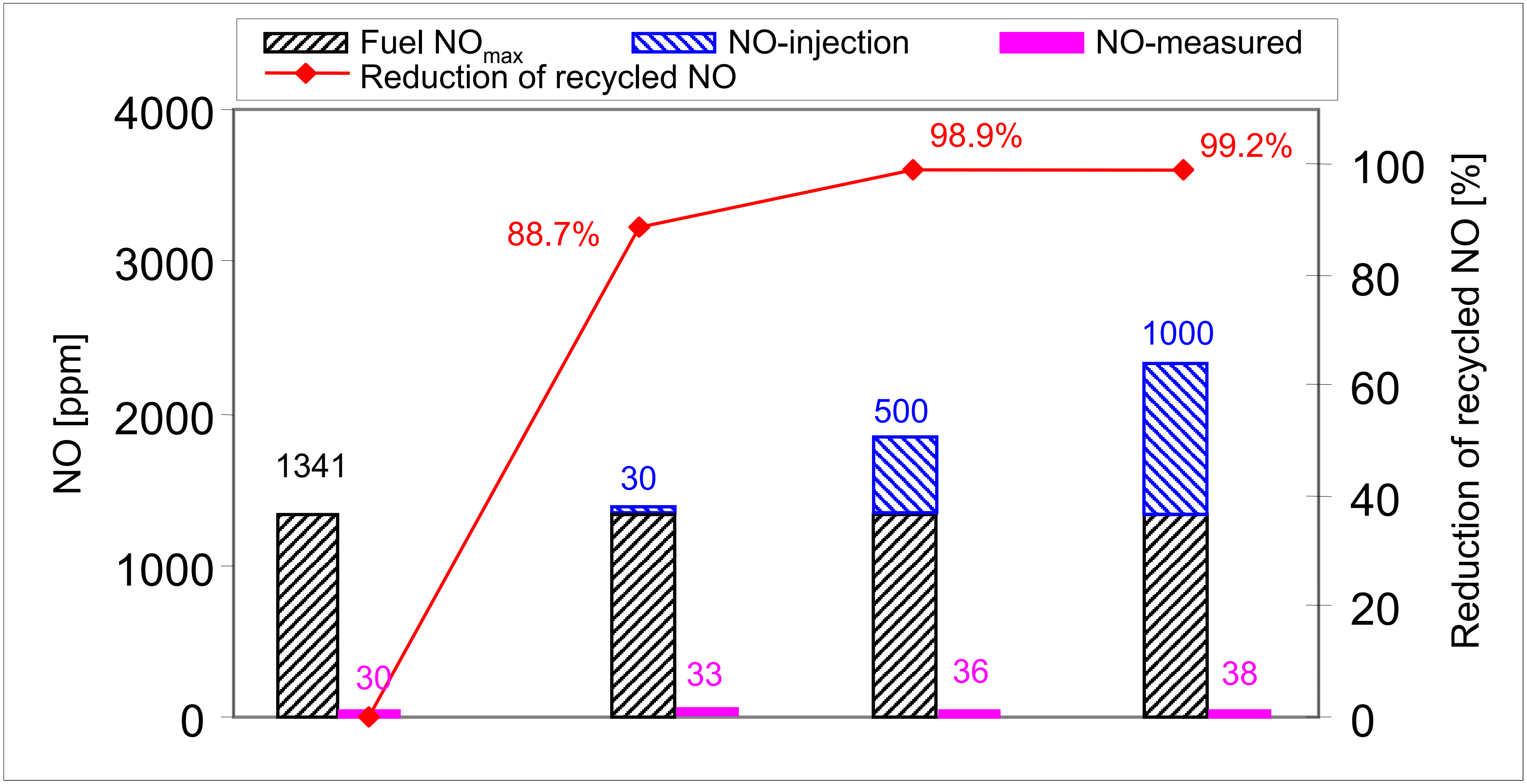
Universität Stuttgart



➢For this burner set-up NO emission with recirculation is much higher than NO emission without recirculation

Staged Combustion (Lausitz Oxy-Coal)

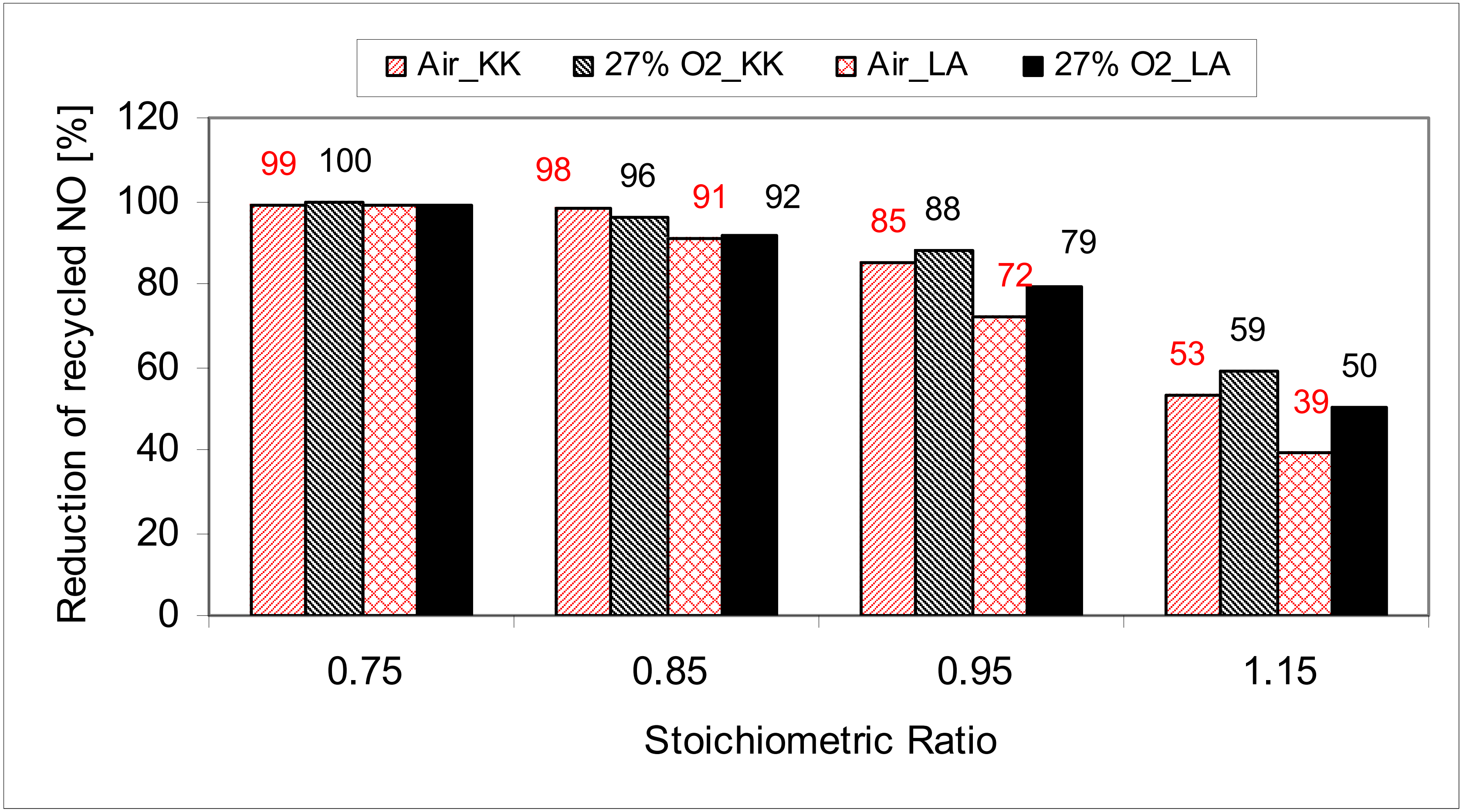
Universität Stuttgart



Burner Stoichiometry = 0.75, Residence time in reduction zone = 3 seconds

➢For this configuration, NO emission is independent of NO injection

Summary-Influence of burner stoichiometry



NO injection = 500 ppm, T_1 = 3 sec

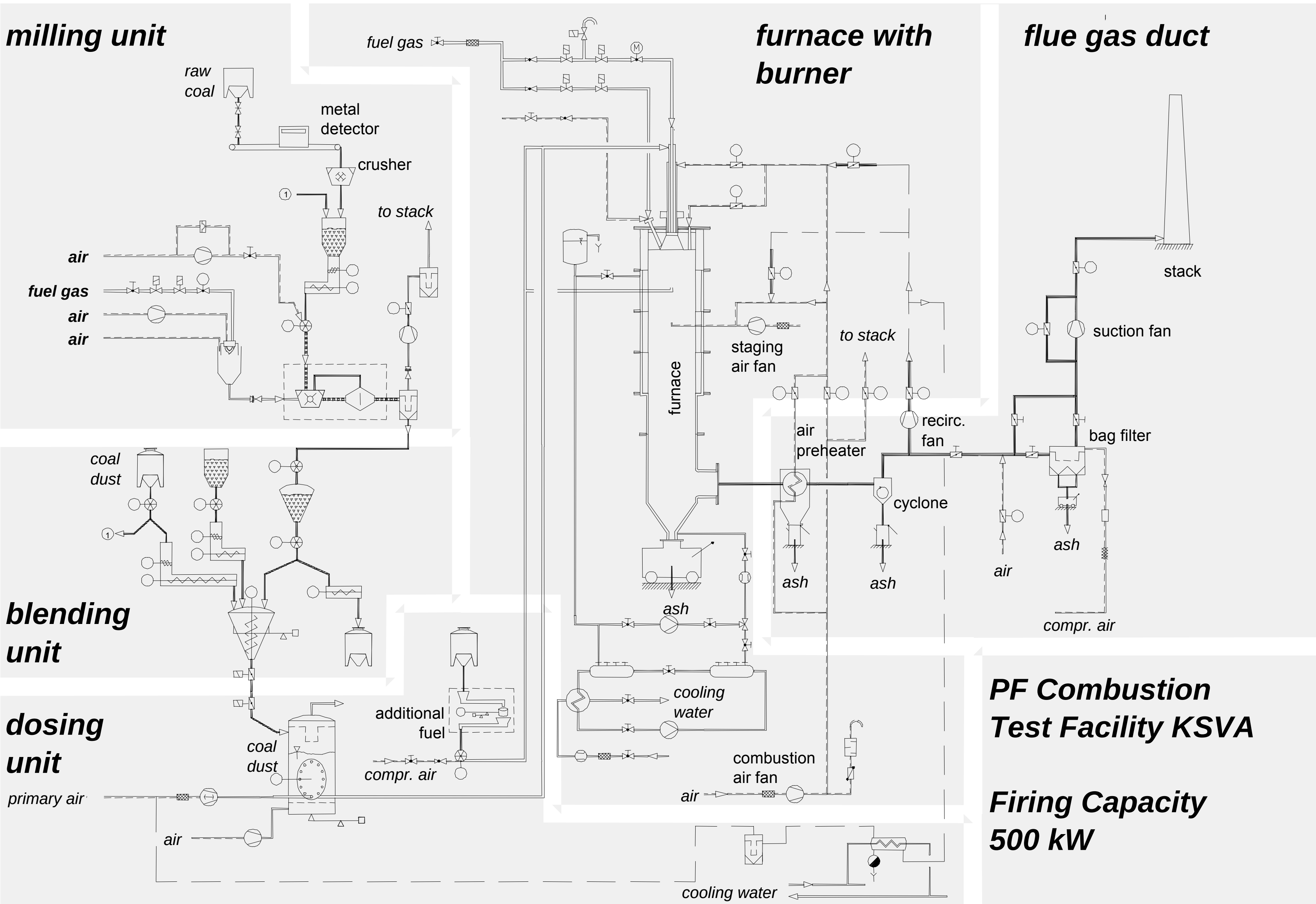
- A burner designed specially for oxy-coal combustion

Universität Stuttgart

Oxyfuel Combustion at existing and adapted $0.5MW_{th}$ test facility of IVD (KSVA)

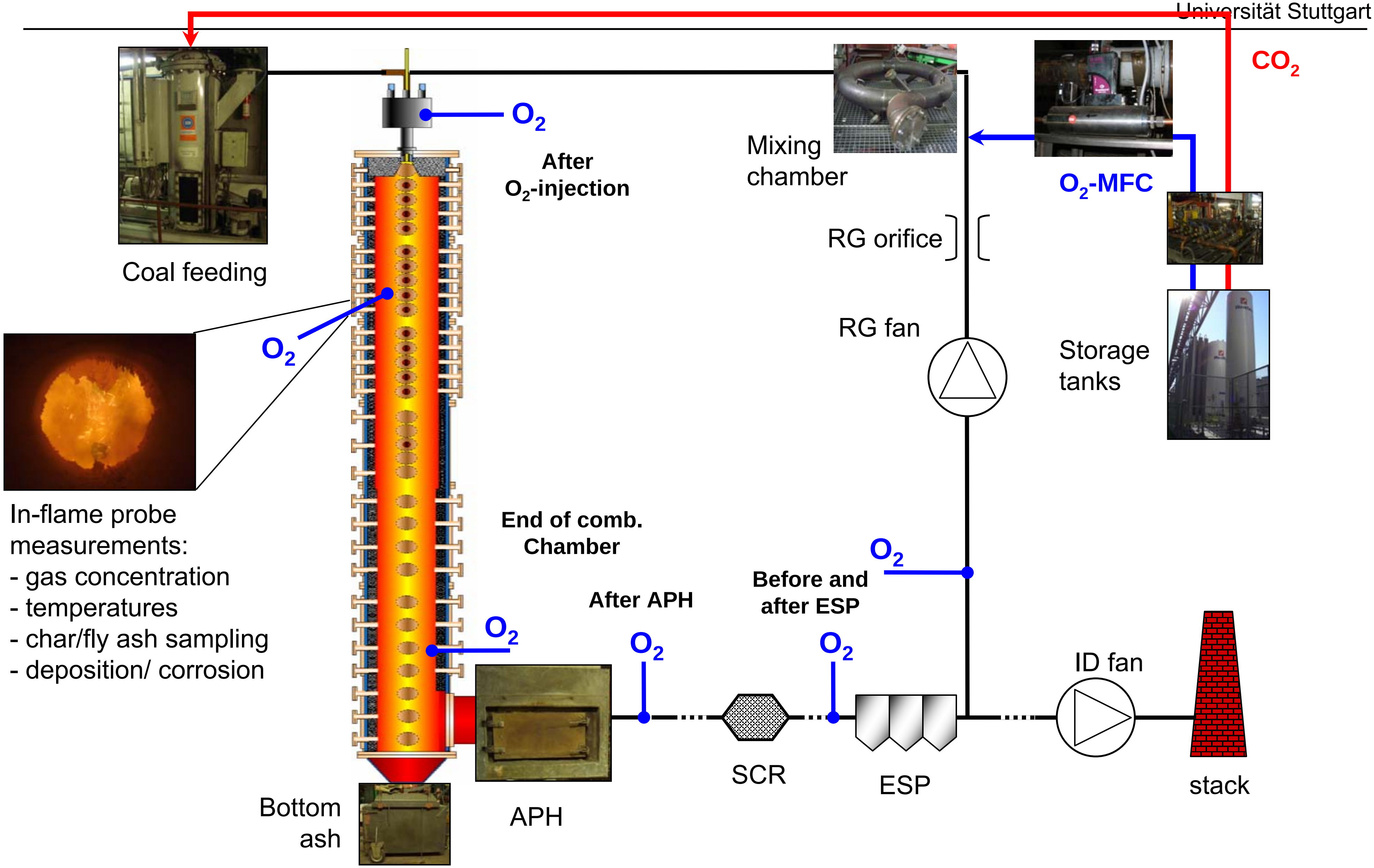
Existing 0.5MW$_{th}$ PF Combustion Test Facility

Universität Stuttgart



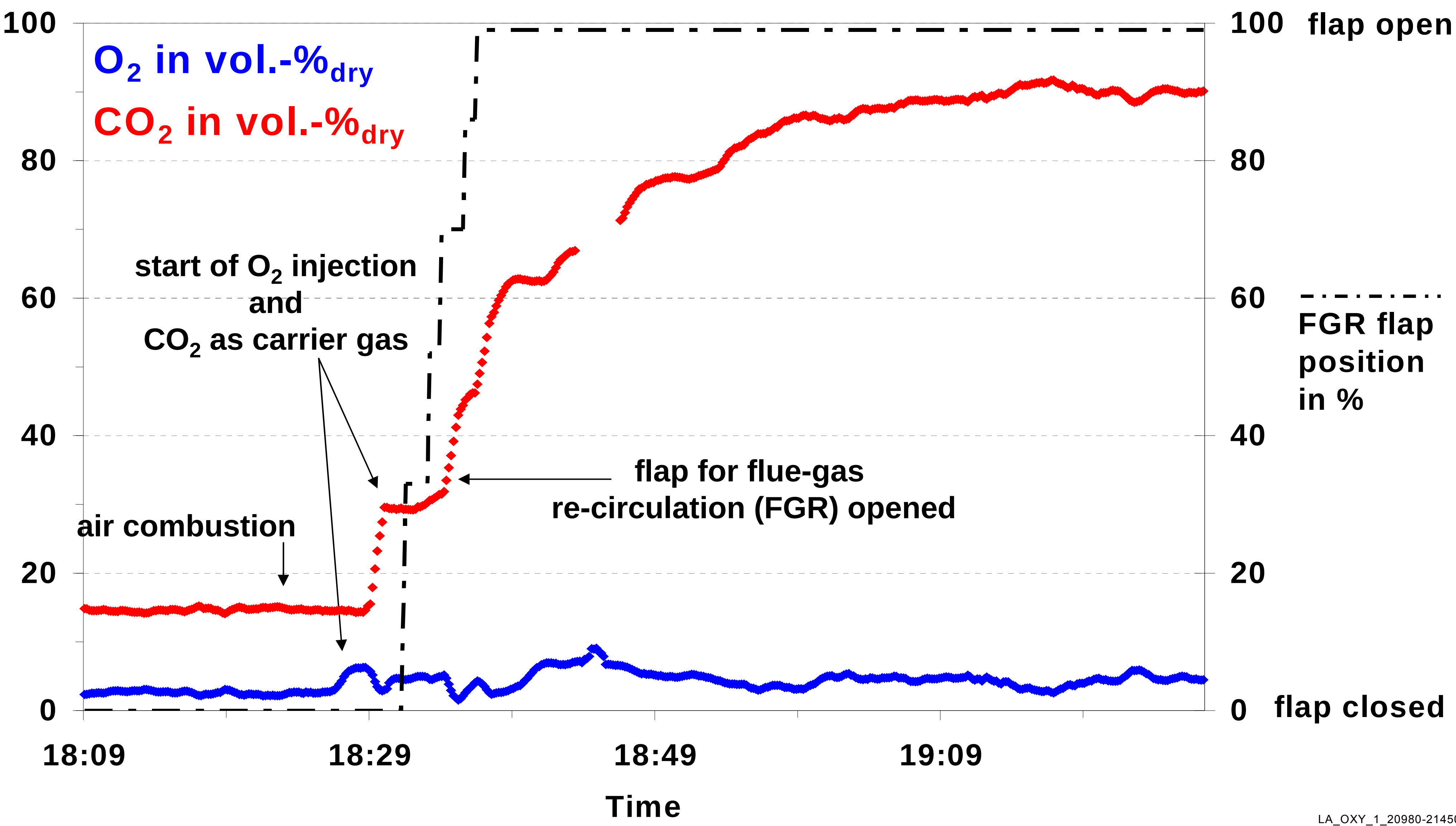
Configuration of 0.5MWth PF Oxyfuel Facility

Universität Stuttgart



Switch from once-through to re-circulation mode (I)

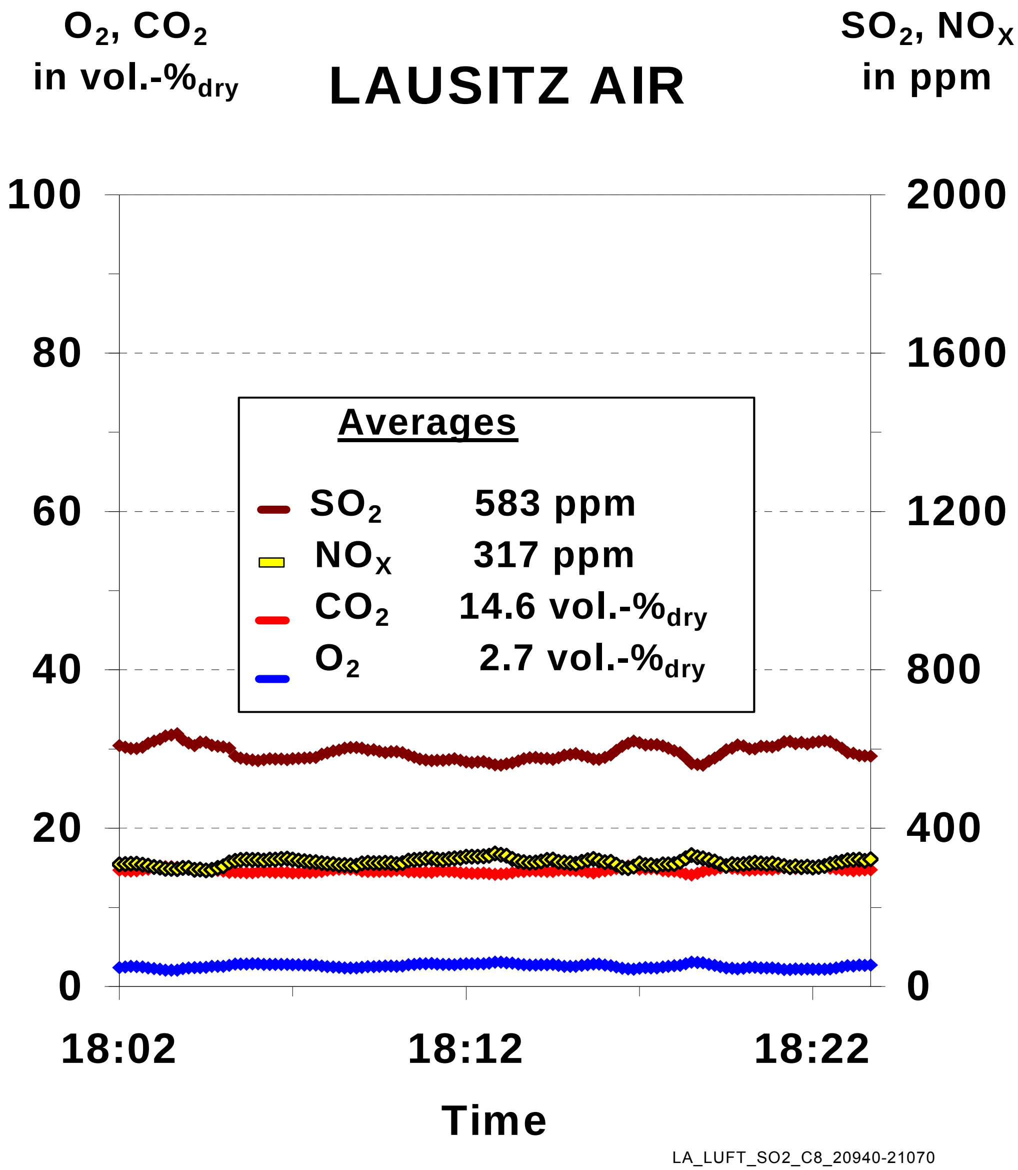
Universität Stuttgart

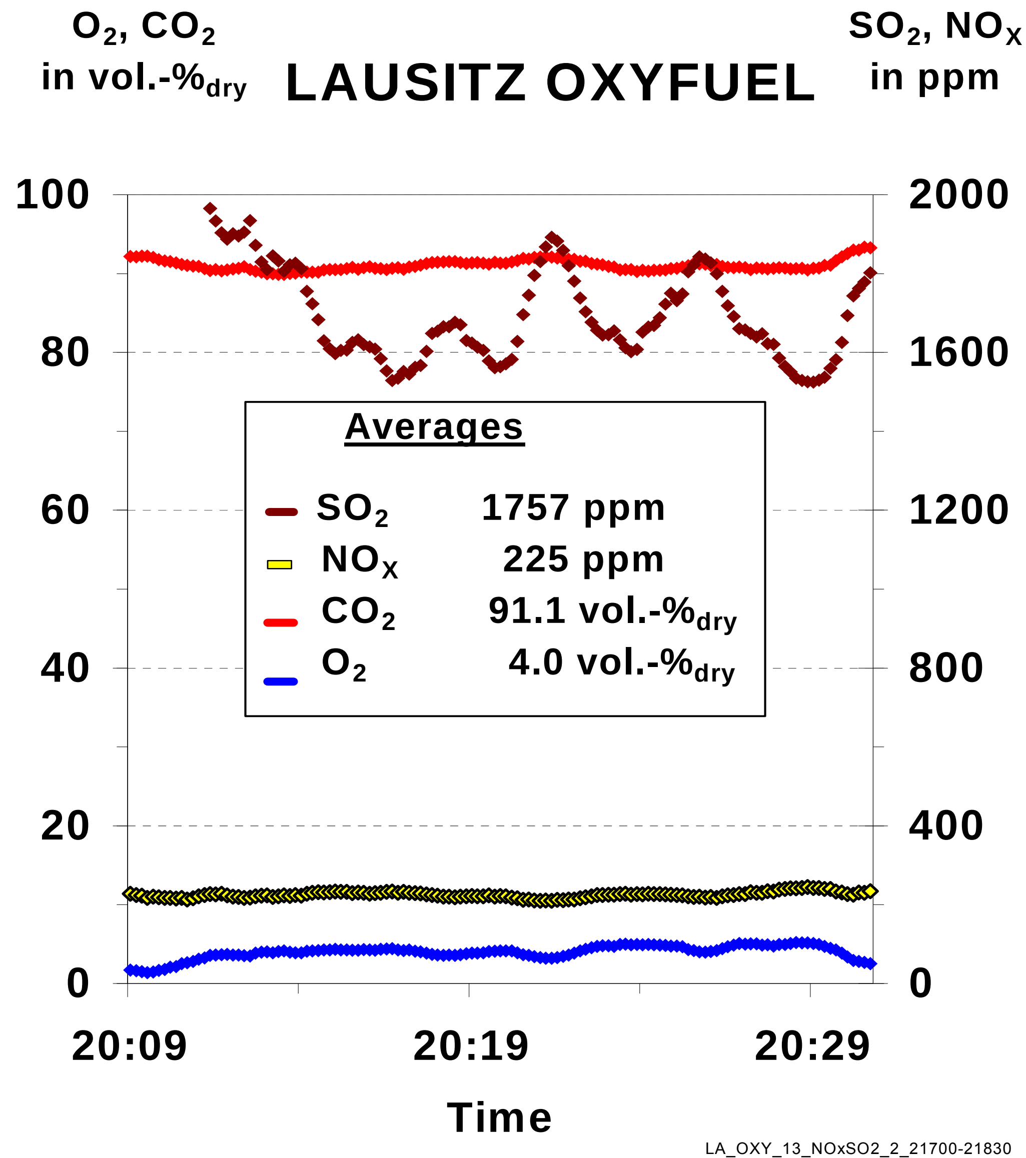


LA_OXY_1_20980-21450

Comparison of emissions at air and oxyfuel conditions

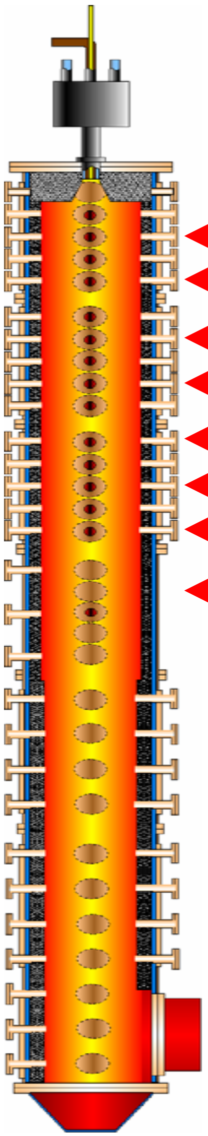
Universität Stuttgart

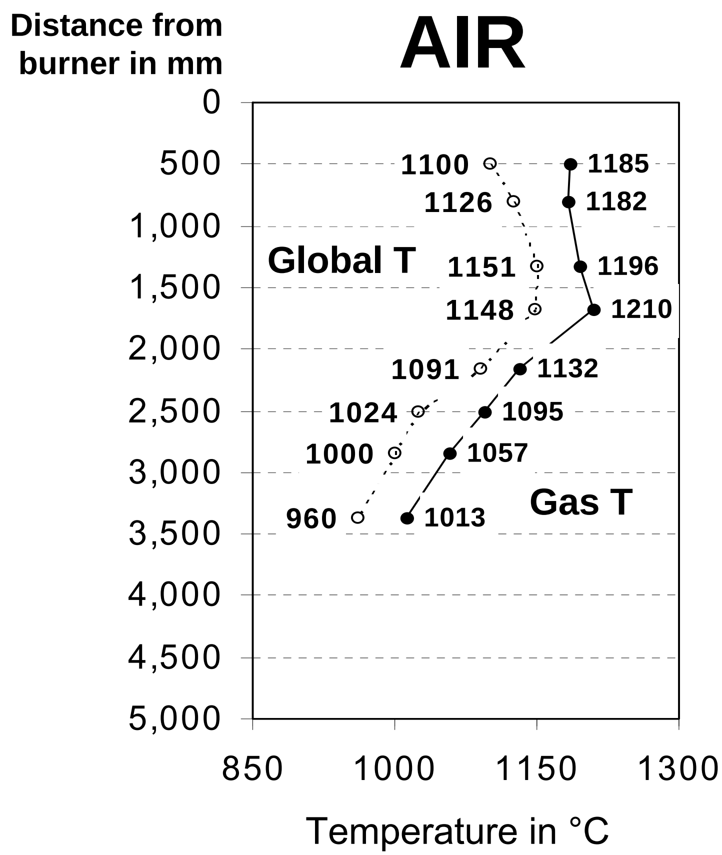


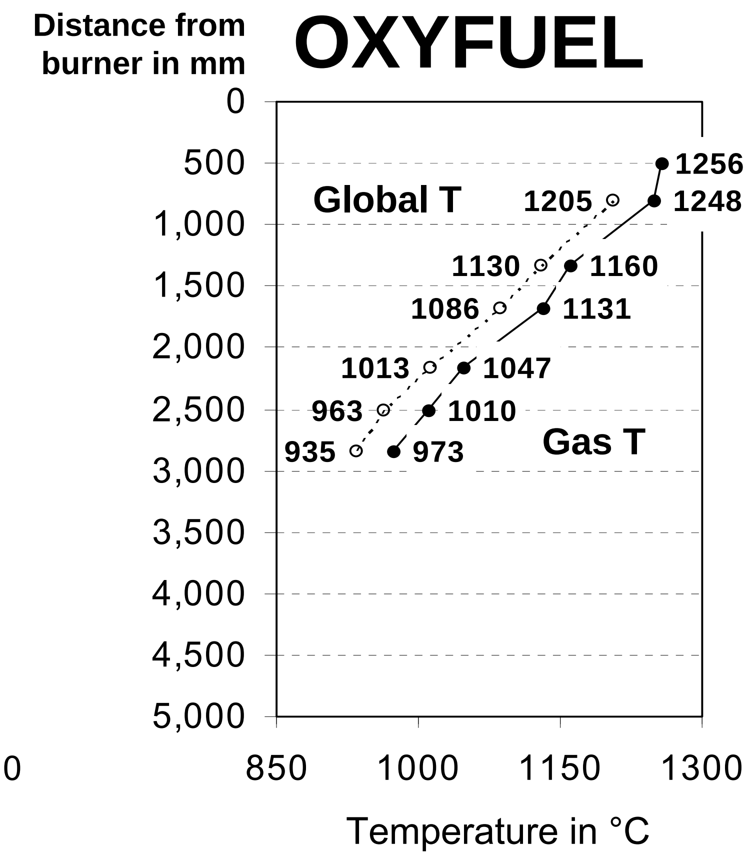


Lausitz pre-dried lignite – combustion temperatures

Universität Stuttgart



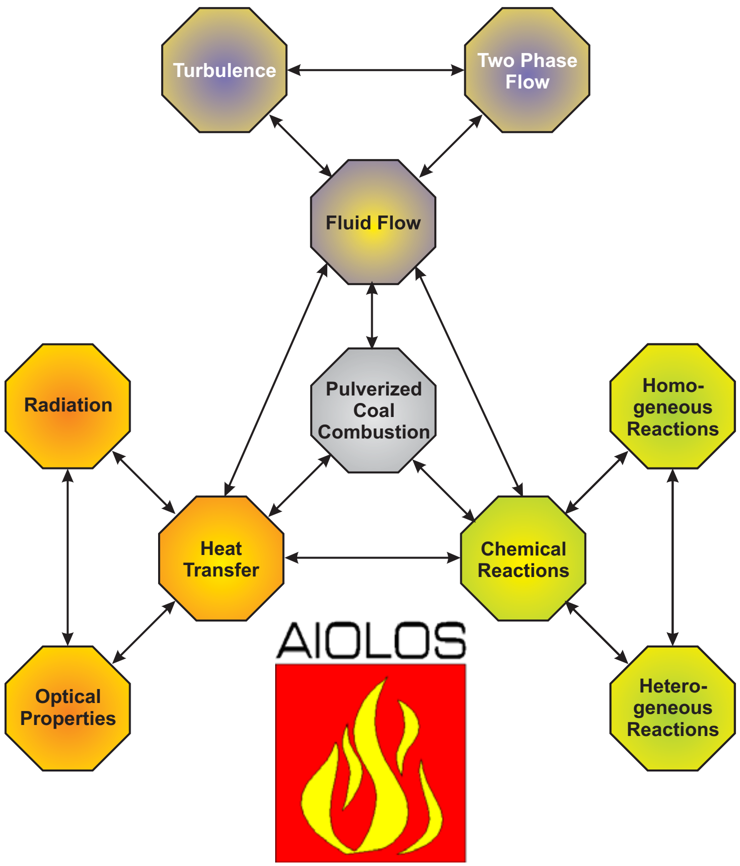


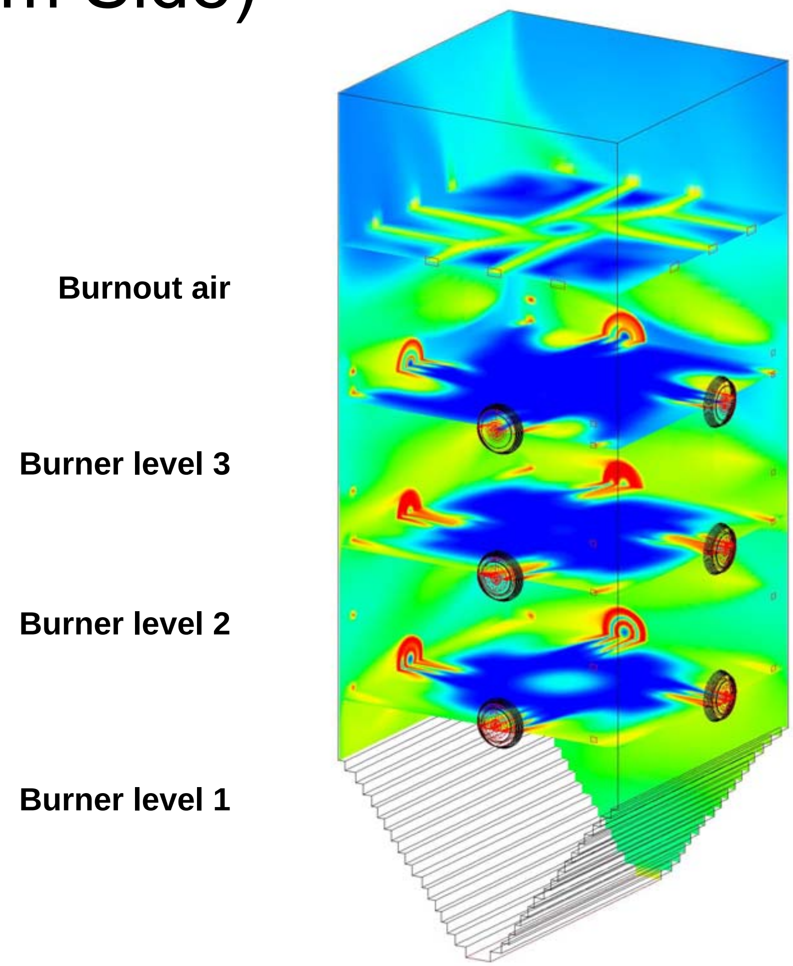


Program Code AIOLOS

Universität Stuttgart

Numerical Modeling and Simulation, combined Simulation (Furnace and Steam Side)





Current Model Developments for Oxy-Fuel

Universität Stuttgart

- Model developments for Oxy-fuel combustion
  - Development of mathematical models for heterogeneous char conversion under Oxy-Fuel conditions, including enhanced gasification reactions
  - Mathematical models for turbulent gas phase reactions:
  - gas phase combustion, NO_x formation and destruction
  - Development of mathematical models for radiative heat transfer in CO_2-enriched atmospheres
  - Validation of new modelling approaches with experimental results
  - Combined coupled approach to furnace and steam generation simulation
- Simulation and optimization of oxyfuel-combustion (0.5MWth...

Overview about CO_2-capture projects at IVD

Universität Stuttgart

Oxyfuel–projects

- ENCAP (IP)
  Pre-combustion CO_2-capture (Oxyfuel, IGCC, others)
- ASSOCOGS (RFCS)
  Oxyfuel
- Oxymod (RFCS)
  CFD-model on oxy-combustion
- OxyBurner (RFCS)
  Low-NO_x coal burner for oxy-combustion

„Limestone“-projects

- C2H (RFCS)
  LEGS with lignite with high moisture content
  Coordination IVD
- ISCC (STREP)
  LEGS with lignite: Focus on calcination with oxygen
  Coordination IVD
- AER-Gas (STREP)
  LEGS with biomass
  Coordination ZSW
- C3-Capture (STREP)
  CO_2-capture by absorption with lime
  Coordination IVD
- AER-GAS II (STREP)
  LEGS with biomass

Post-Combustion-projects

- CASTOR (IP)
  Post-combustion CO_2-capture
- FLUEGAS (Industrial)

IP Integrated project (6^{th} EC framework program)
STREP Specific targeted research project (6^{th} EC framework program)
RFCS Research fund for coal and steel

as from July 2006

C E T C CANMET ENERGY TECHNOLOGY CENTRE

C E T C CANMET ENERGY TECHNOLOGY CENTRE

Modeling, Design, and Pilot-Scale Experiments of CANMET's Advanced Oxy-Fuel/Steam Burner

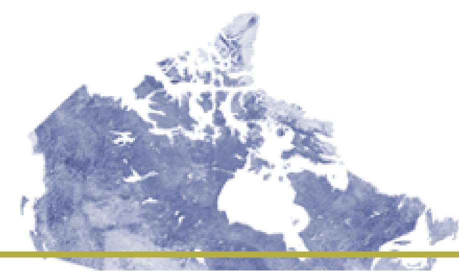
CLEAN ENERGY TECHNOLOGIES

K. Zanganeh, C. Salvador, and M. Mitrovic

Zero-Emission Technologies Group, CEPG

2nd IEA GHG Oxy-Combustion Workshop

January 25-26, 2007

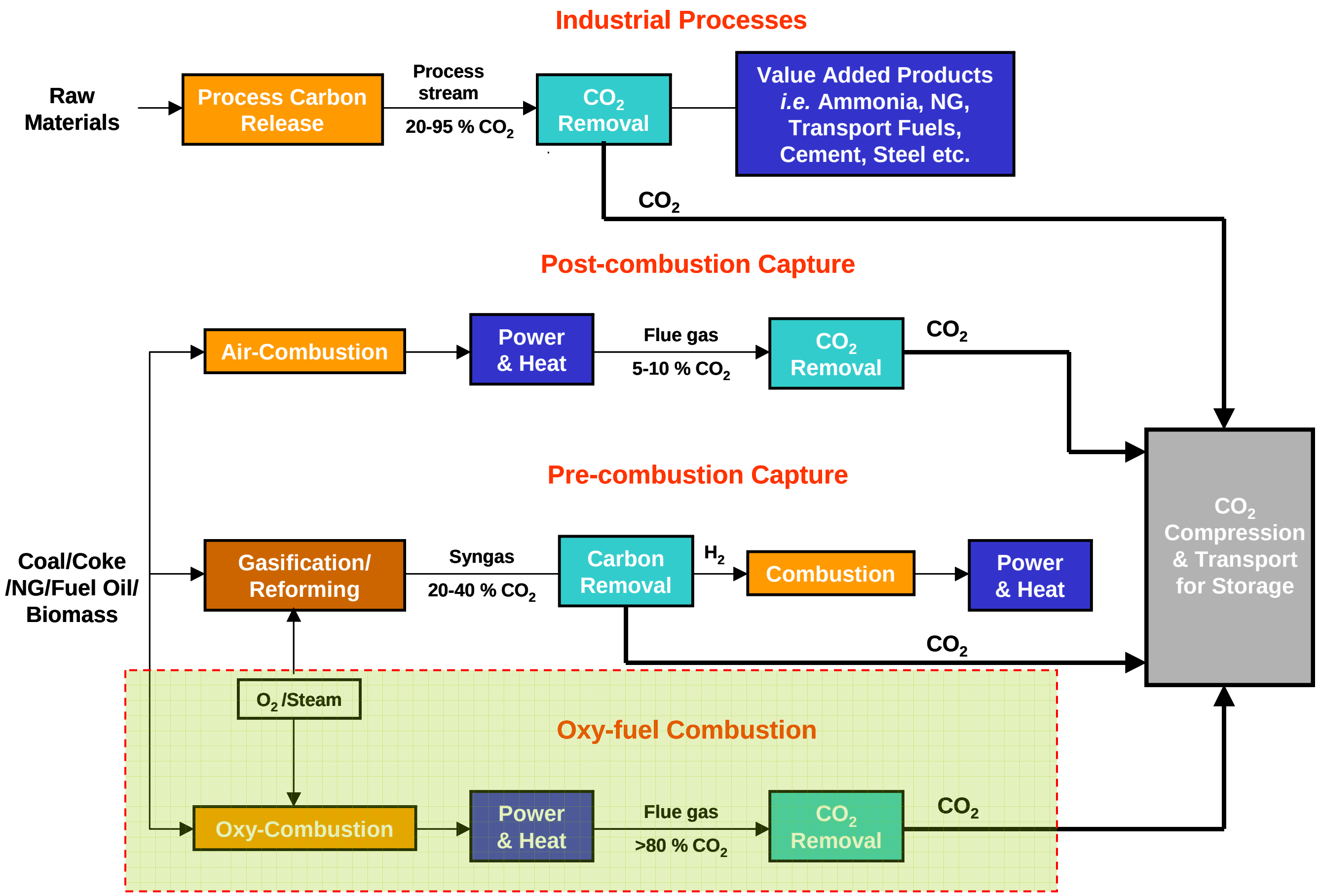


Natural Resources Canada Ressources naturelles Canada

Canada

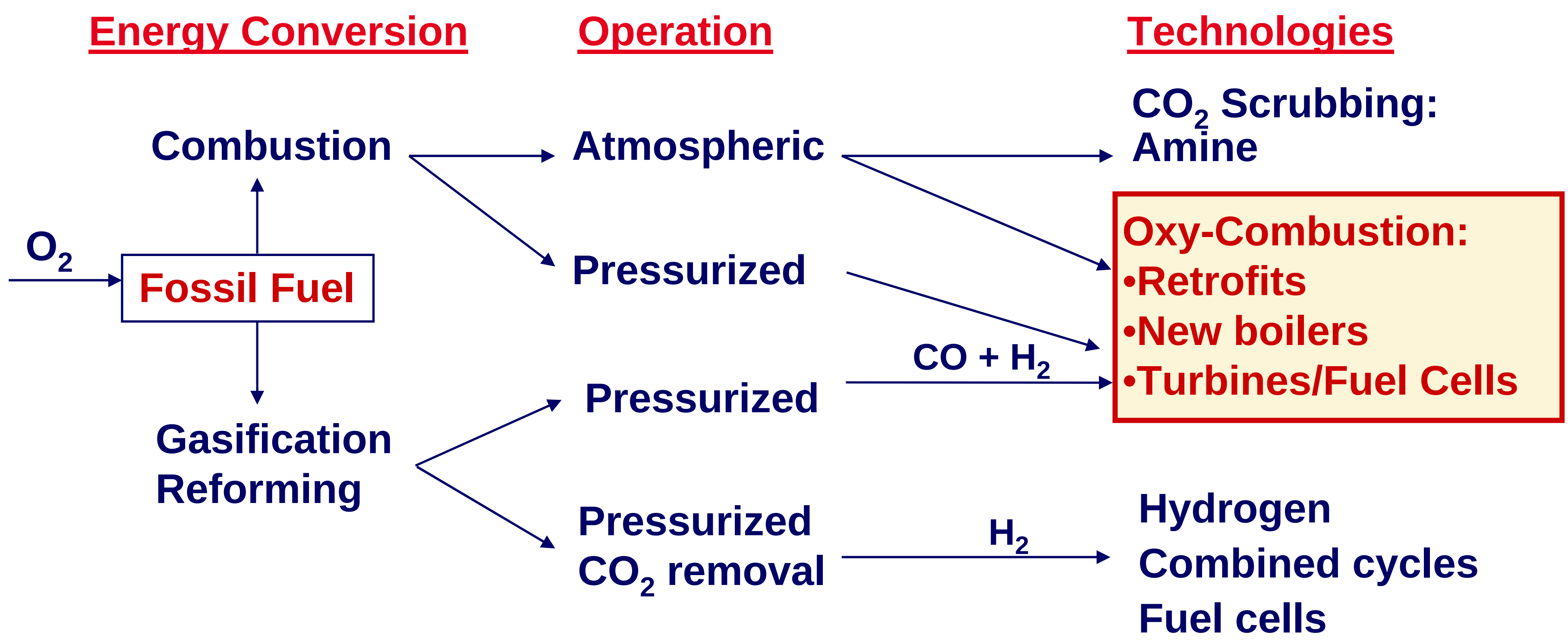
Technology Background

- **Clean fossil fuel combustion with CO_2 capture pathways**



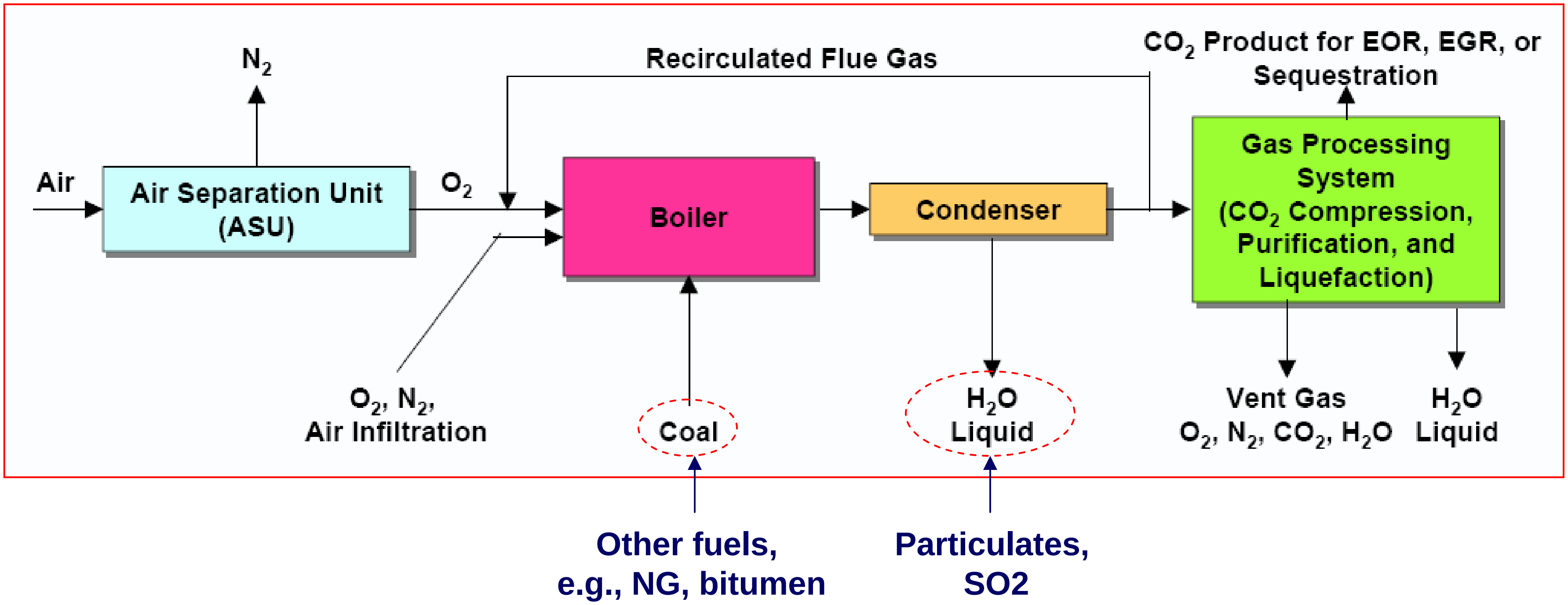
Technology Background (*cont…*)

- Oxy-fuel combustion pathways



Technology Background (*cont…*)

- **Oxy-fuel combustion systems**
  - ***1st generation*** **oxy-fuel combustion systems - Flue gas is recycled to control the combustion temperature**

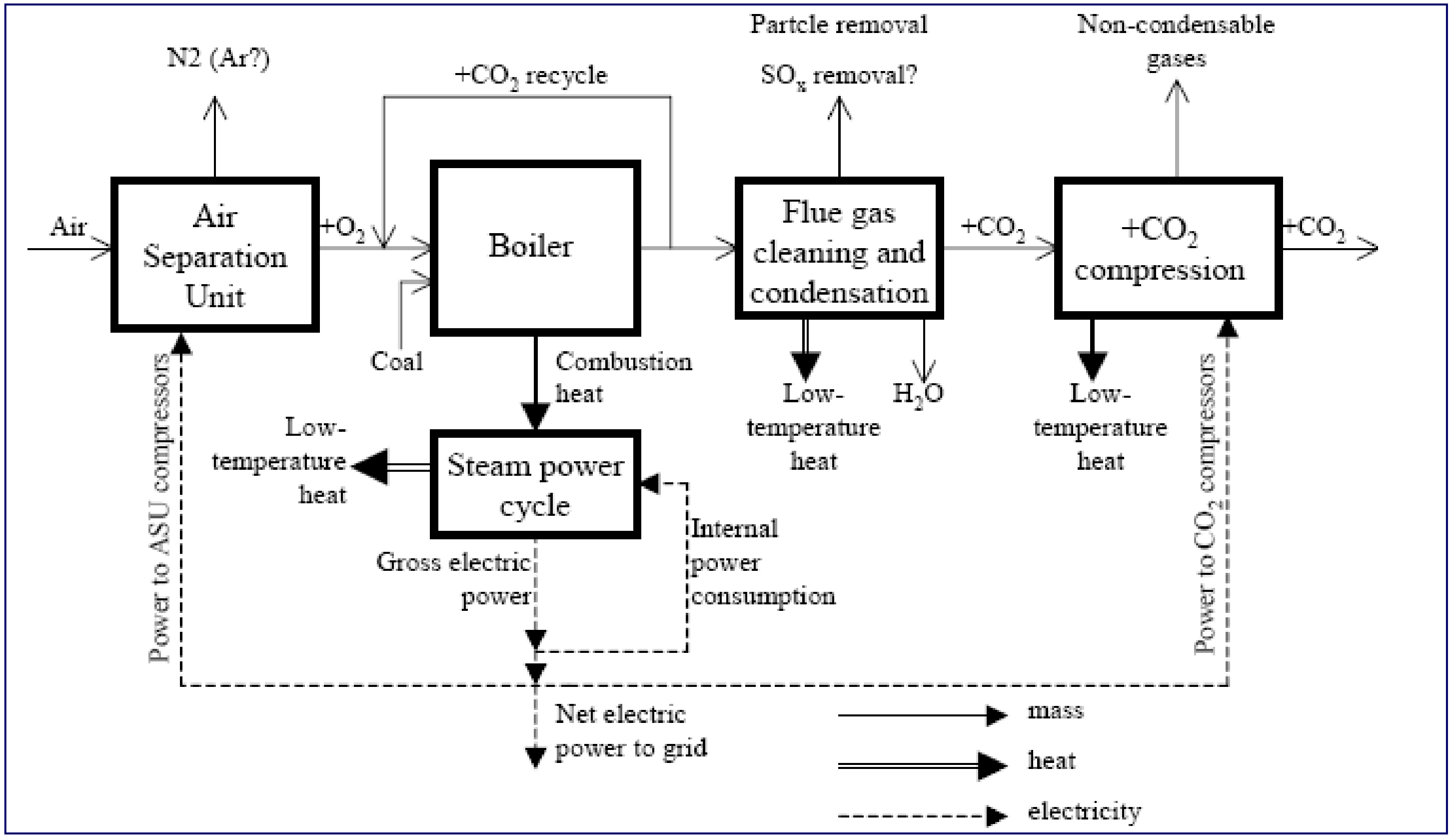


Technology Background (*cont…*)

- No reduction in unit size/volume compared to air-fired combustion (up to flue gas branch point)
- No energy efficient integration and optimization of the process
- No efficient recovery of low temperature heat
- Need to design the whole plant as a gas-tight system
  - CO_2 and hot gas leakage out
- Operational safety considerations
  - Plant has to operate at slightly negative pressure
    - Air leakage in
- Need for flue gas recycle to transport coal from the mills
  - Need for gas-tight mills
  - Need for treatment of the primary recycle flow, etc

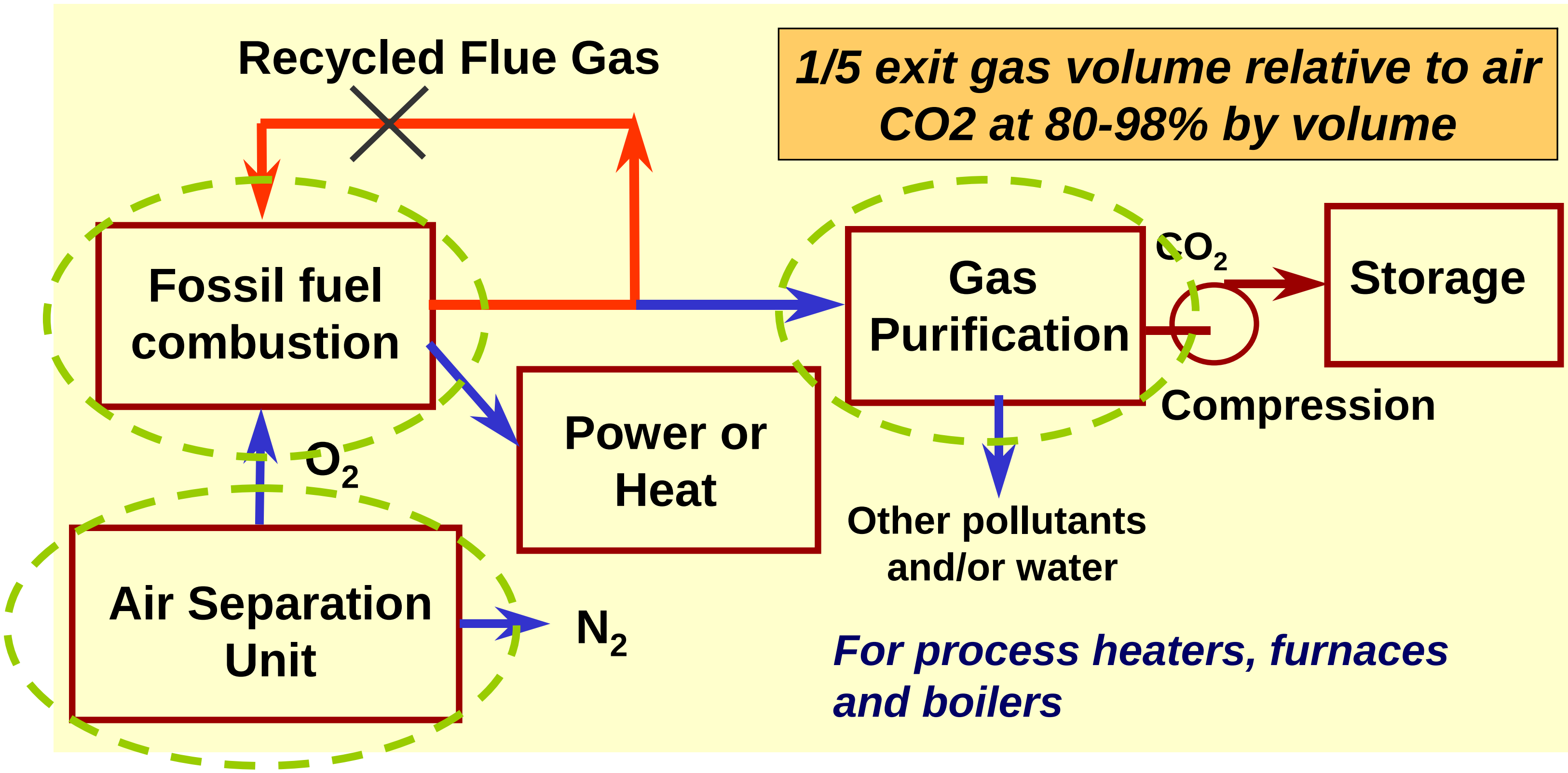
Technology Background (*cont…*)

- *2nd generation* oxy-fuel combustion systems - Energy efficient integration and optimization of the process, recovery of low temperature heat



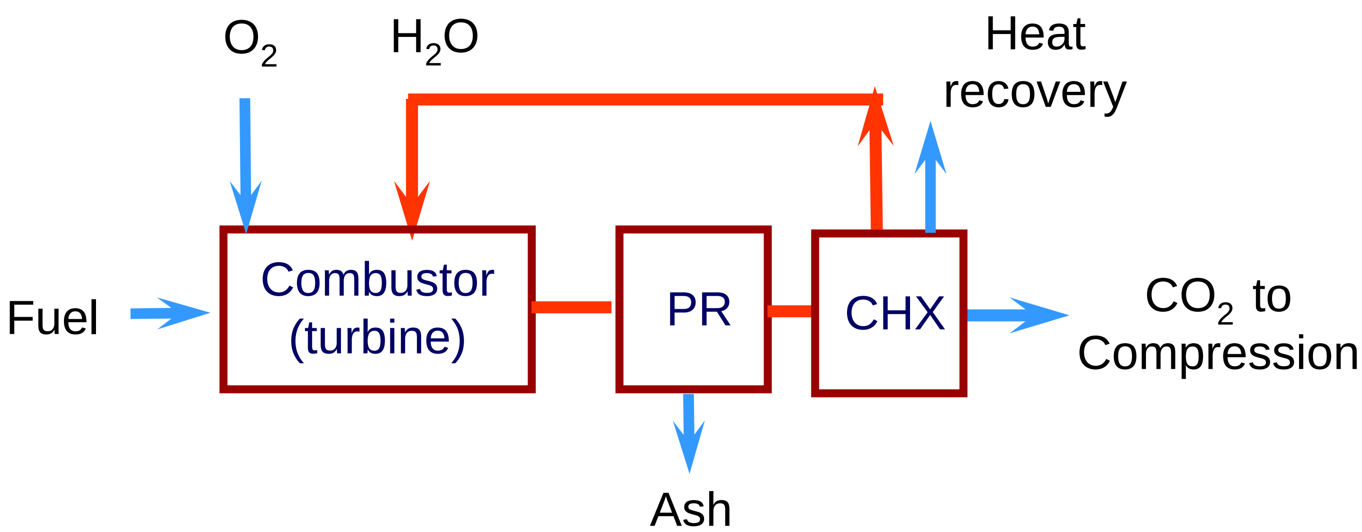
Technology Background (*cont…*)

- *3rd generation* oxy-fuel combustion systems – Minimizing or eliminating the flue gas recycle (no FGR)



Technology Background (*cont…*)

- ***Low NOx & excess O_2,***
- ***Higher radiative & convective heat transfer,***
- ***process model, CFD, system and component design***



Hydroxy-Fuel Technology Development

Motivation:

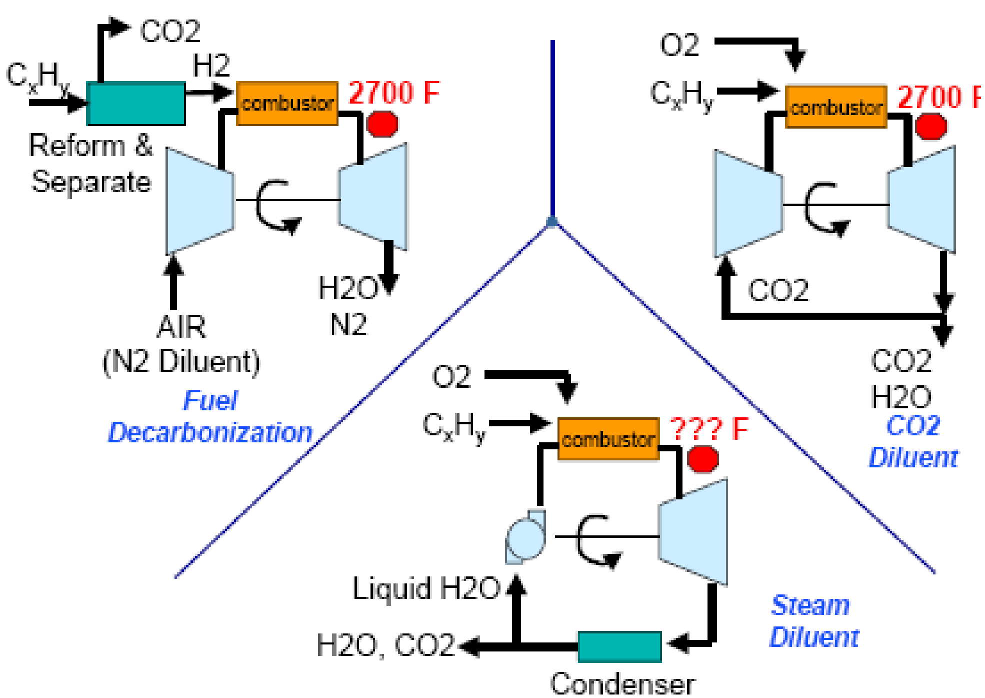
- Develop the technology base necessary for the implementation of efficient zero-emissions fossil fuel systems

Overall Objectives:

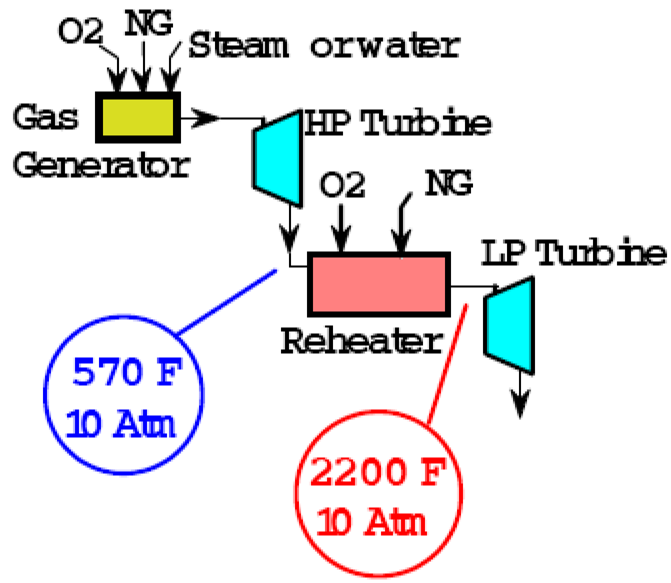
- Investigate the feasibility of hydroxy-fuel combustion for the 3rd generation of oxy-fuel systems
- Investigate the reduction in size and capital cost of equipment
- Use of water/steam, preferably with no FGR, to moderate the flame temperature

Hydroxy-Fuel Technology Development (*cont…*)

- **Selected power cycles**



Advanced Steam Generators, Richards et. al, NETL



A reheat cycle with steam or water as temperature moderator

Development, Design and Integration

Zero-Emission Oxy-Steam Combustion

Process & System Design

Oxy-Steam Burner

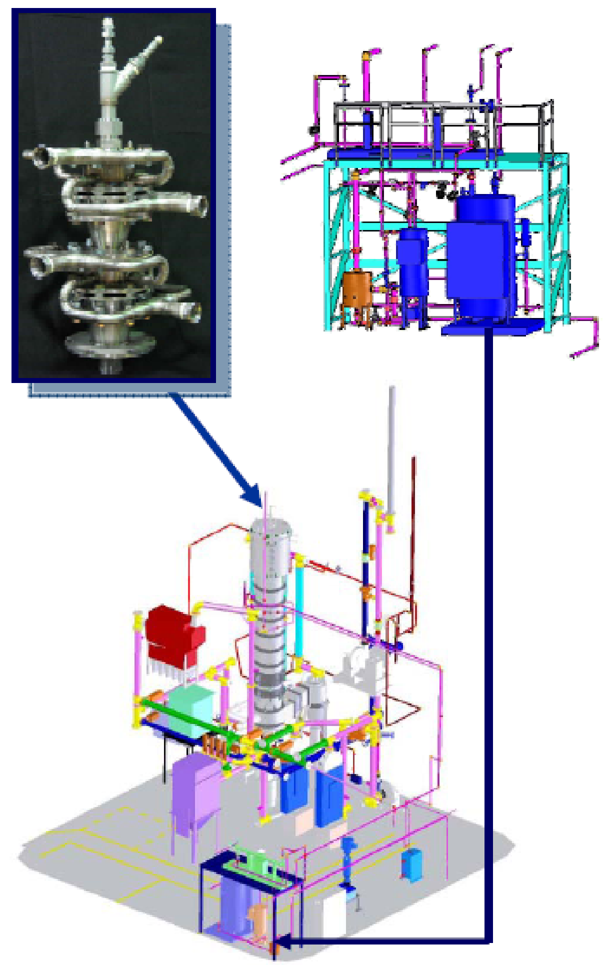
VC Plant

Steam Generation Delivery System

Overall System Integration

Optimization & Testing

Scale-Up

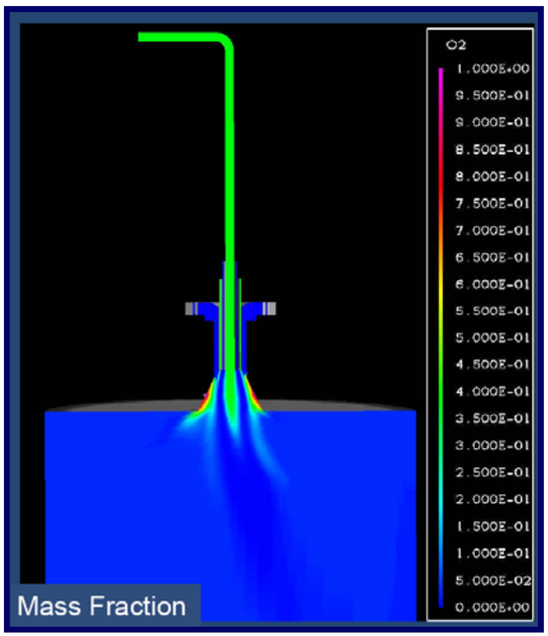


Development, Design and Integration (*cont…*)

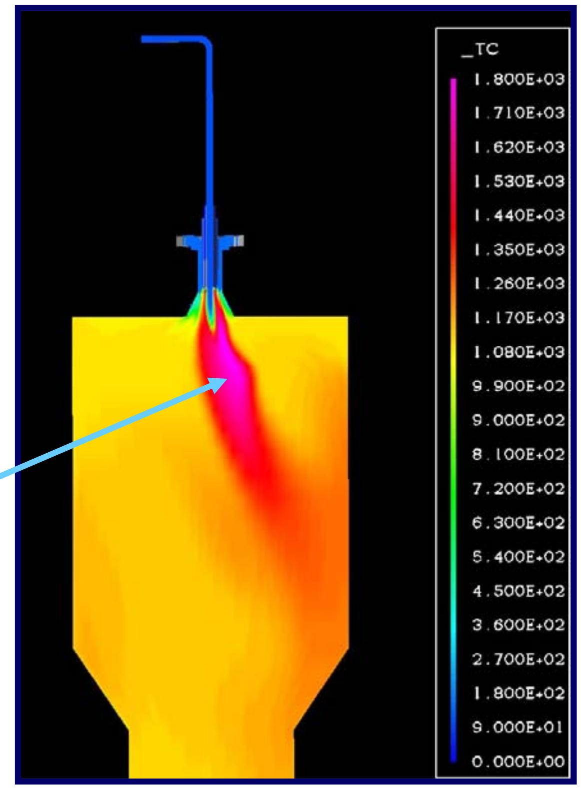
CFD Simulation

• Gauged the suitability of a test burner for hydroxy-fuel combustion.

O_2 distribution



Temperature Profile

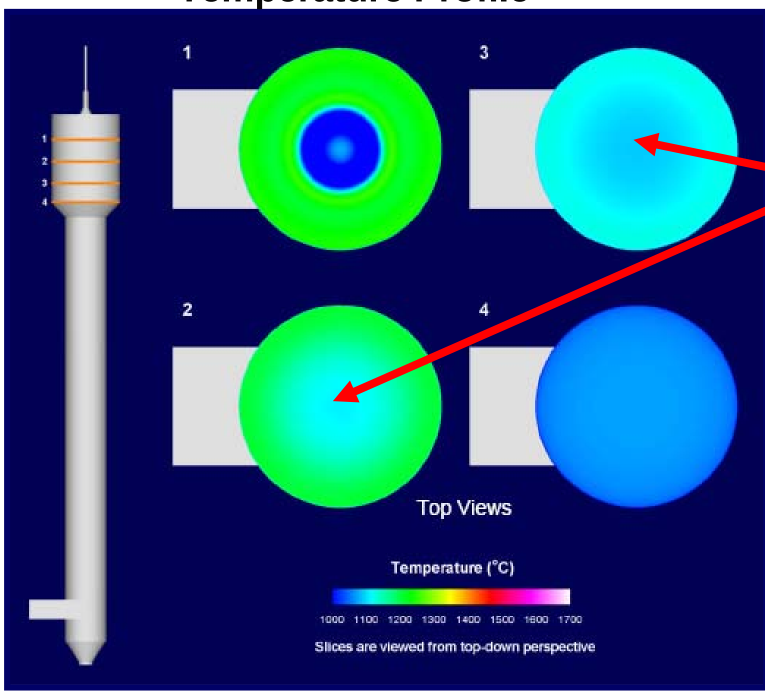


Flame leans to one side.

Development, Design and Integration (*cont…*)

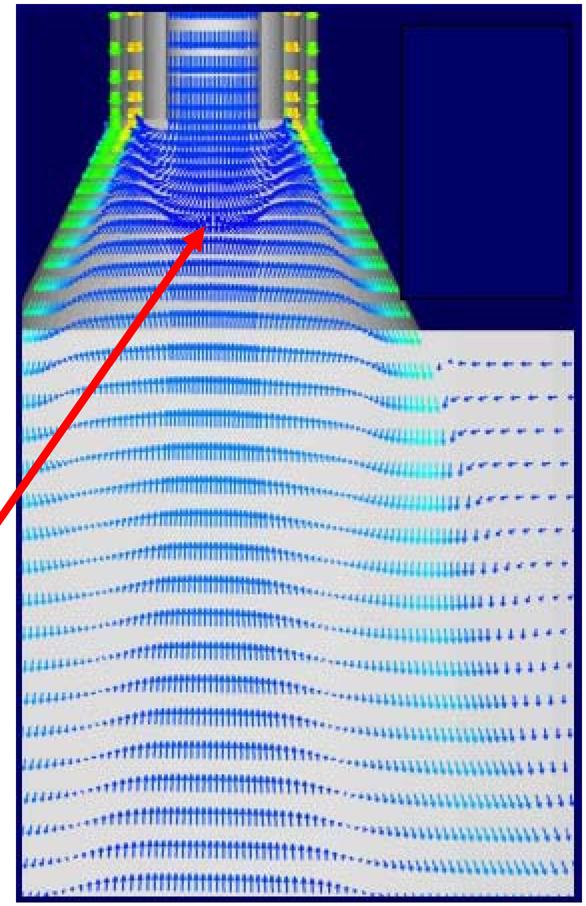
CFD Simulation

Temperature Profile



Uniform temperature distribution

Stagnation Point



Vector Plot of Speed

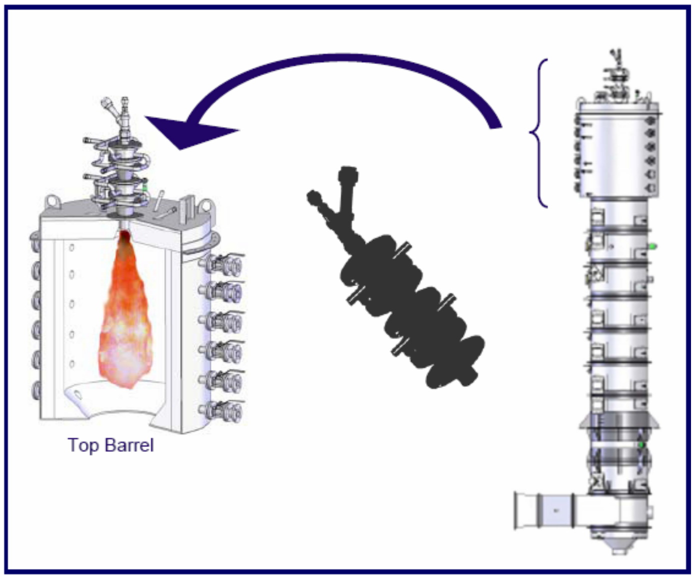
Development, Design and Integration (*cont…*)

- **Burner prototype**
  - **Firing rate: 0.3MWth (1MMBtu/hr)**
  - **Fuels:**
    - Natural gas
    - Oil, Emulsion
    - Pulverized coal and coal slurry
  - **Operational modes**
    - O2/steam
    - O2/RFG
    - O2/CO2
    - Air
    - Enriched air
    - O2/steam/RFG
    - O2/steam/CO2
  - **Variable secondary & tertiary streams**
  - **Independent secondary & tertiary swirl**

Development, Design and Integration (*cont…*)

Integration with Vertical Combustor

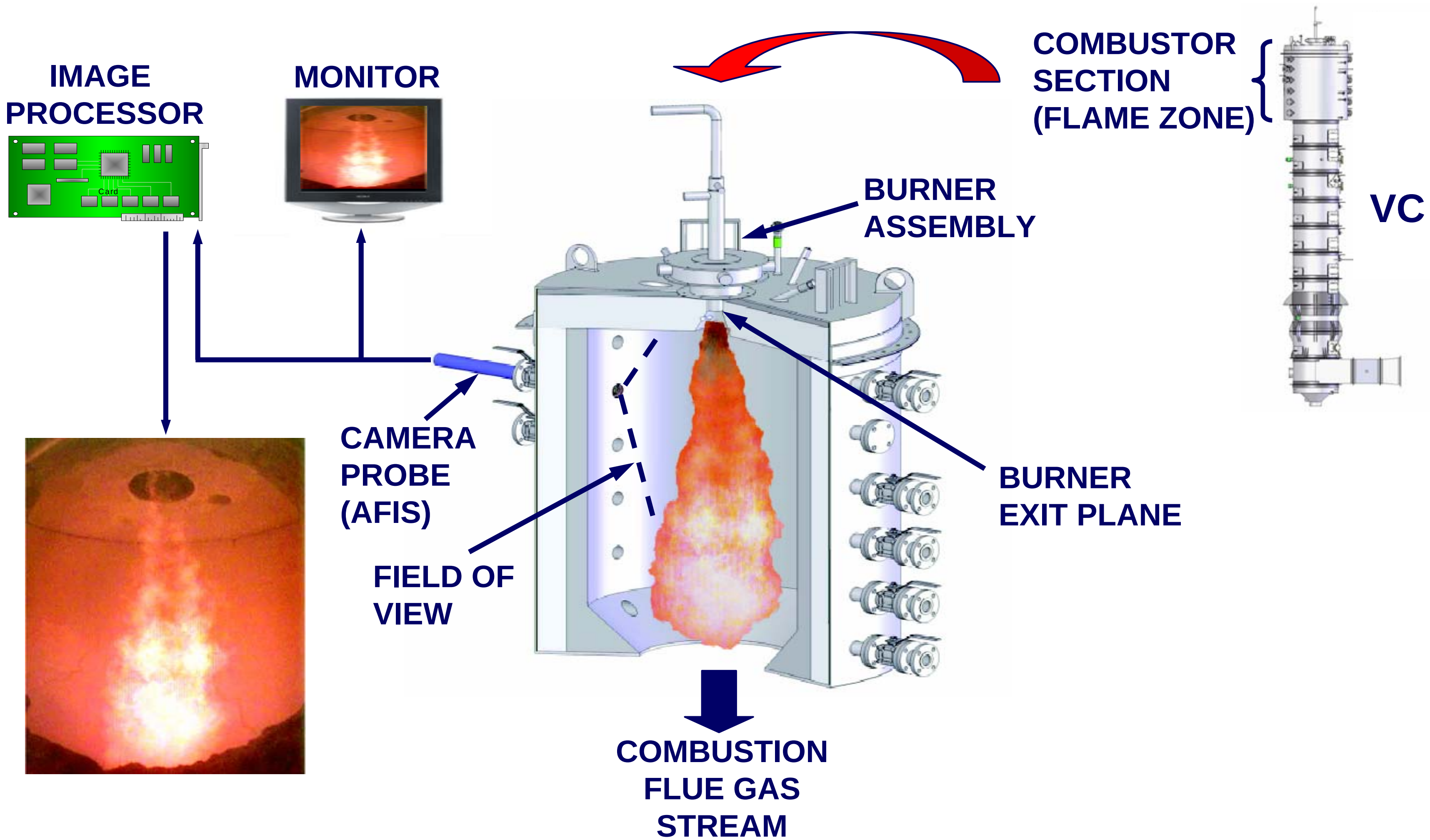
- **Steam generation system**
- **O_2 and steam piping design**
- **Instrumentation and control**
- **Graphical user/control interface**

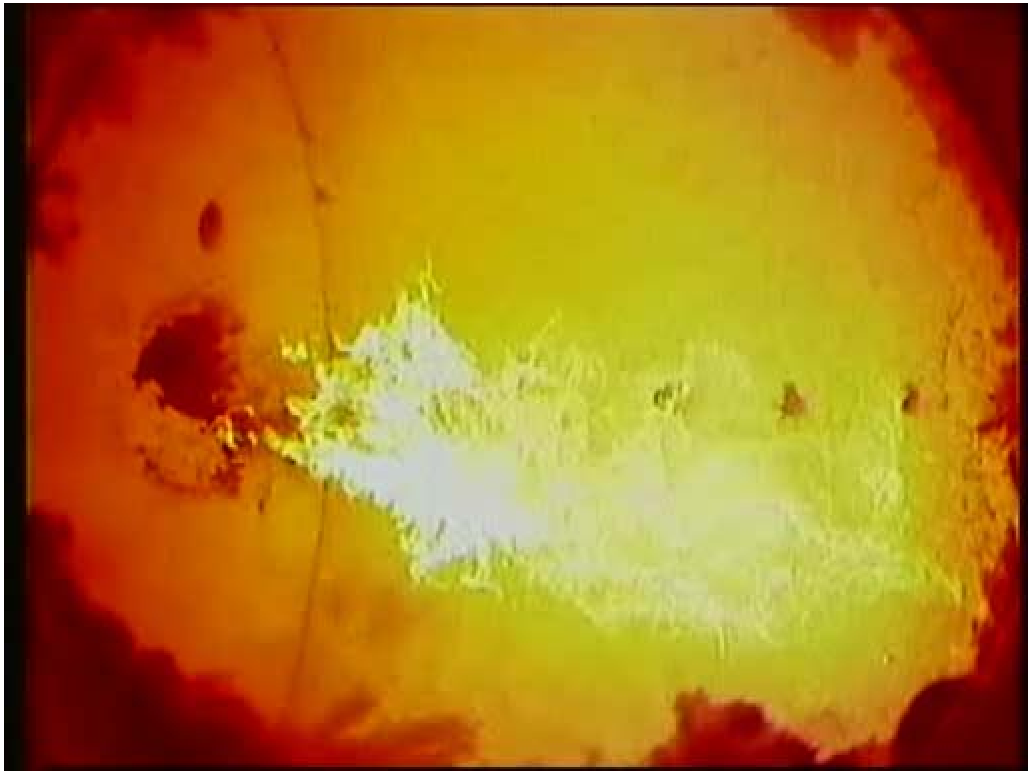


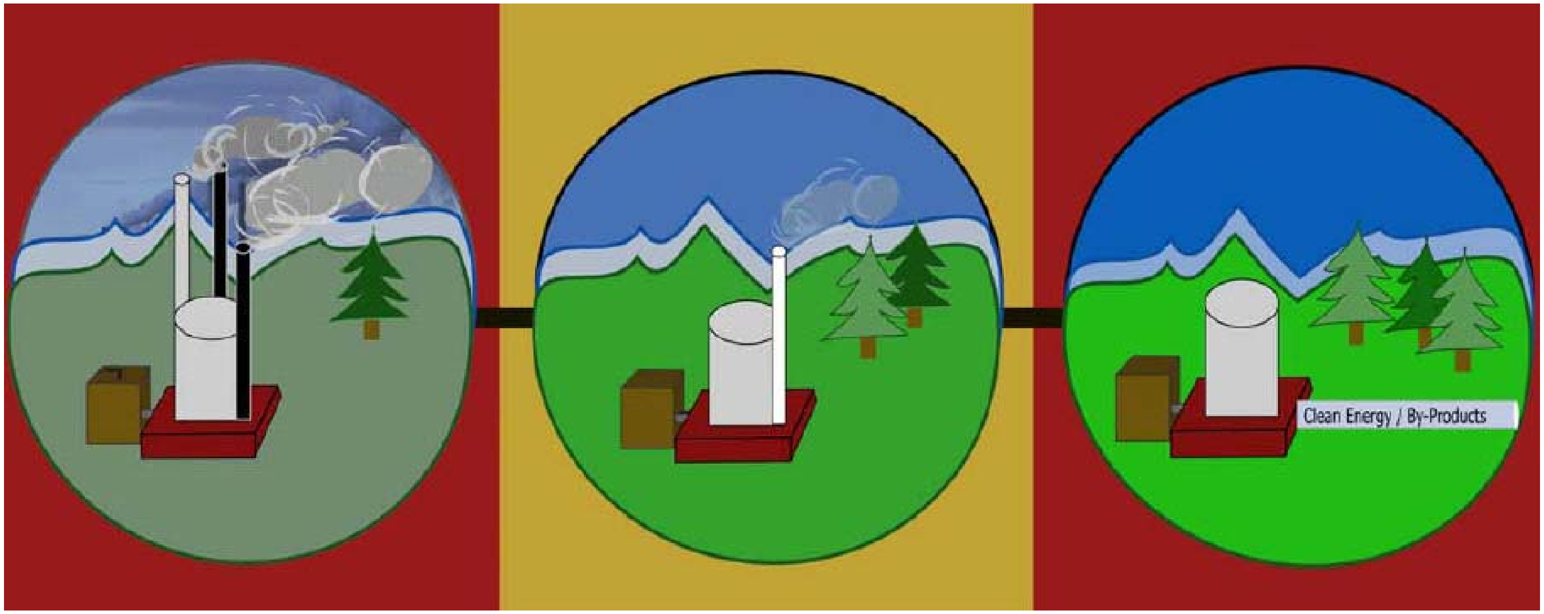
Concluding Remarks

- **All aspects of hydroxy-fuel process design, technology development, and implementation were performed at CANMET**
  - **i.e., design, manufacturing, system integration, and pilot-scale testing**
- **The preliminary pilot-scale test results are very encouraging**
- **Economic and scale up studies will be performed after completion of all pilot-scale tests**
- **The oxy-fuel/steam burner design is novel and we are in the process of applying for a patent**

Advance Flame Imaging System (AFIS)







Thank You

2nd Workshop

IEAGHG International Oxy-Combustion Network

Hilton Garden Inn

Windsor, CT, USA

25th and 26th January 2007

Purification of Oxyfuel-Derived CO_2 for Sequestration or EOR

Vince White

Air Products PLC, UK

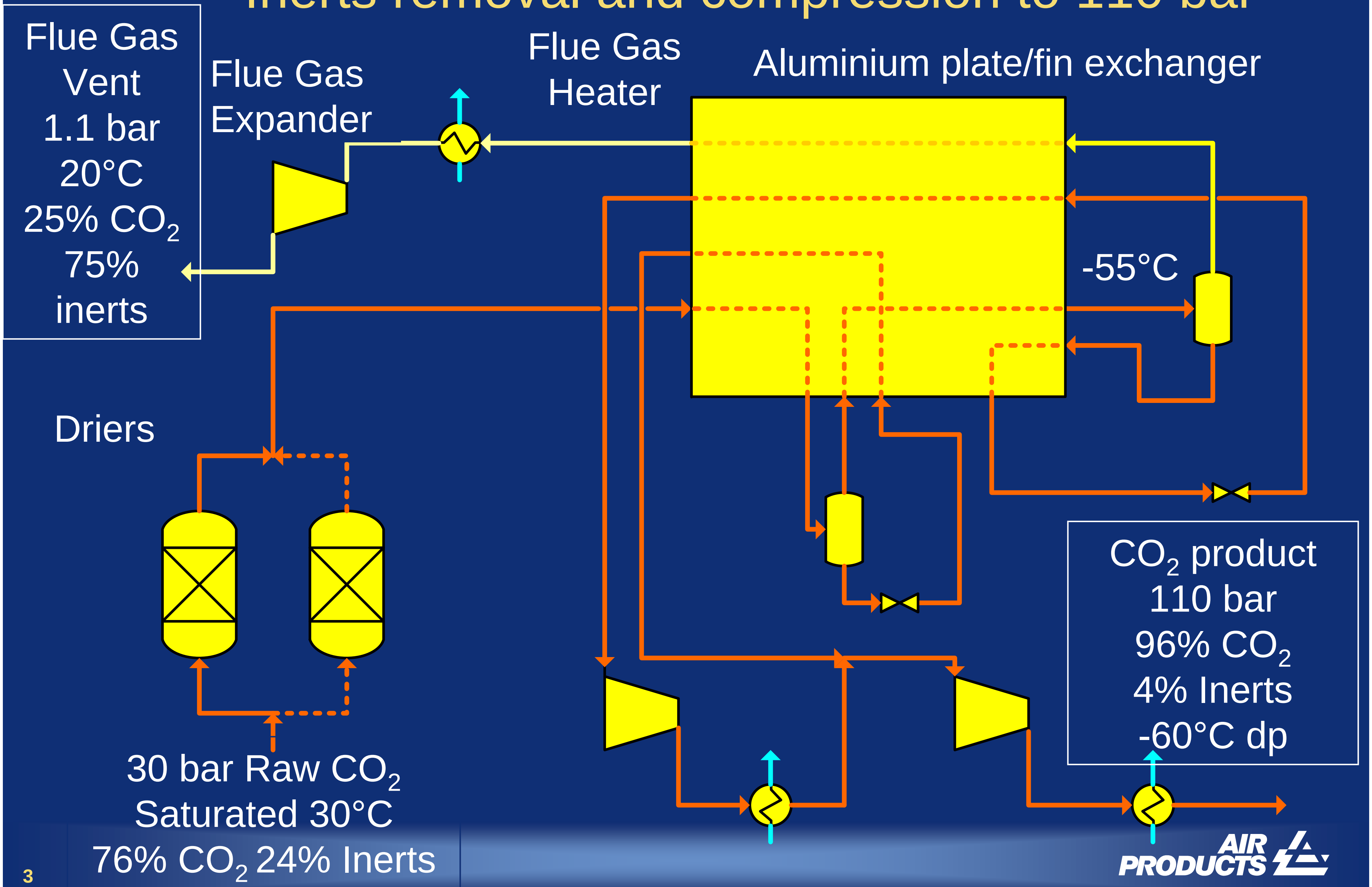
25th January 2007

AIR PRODUCTS

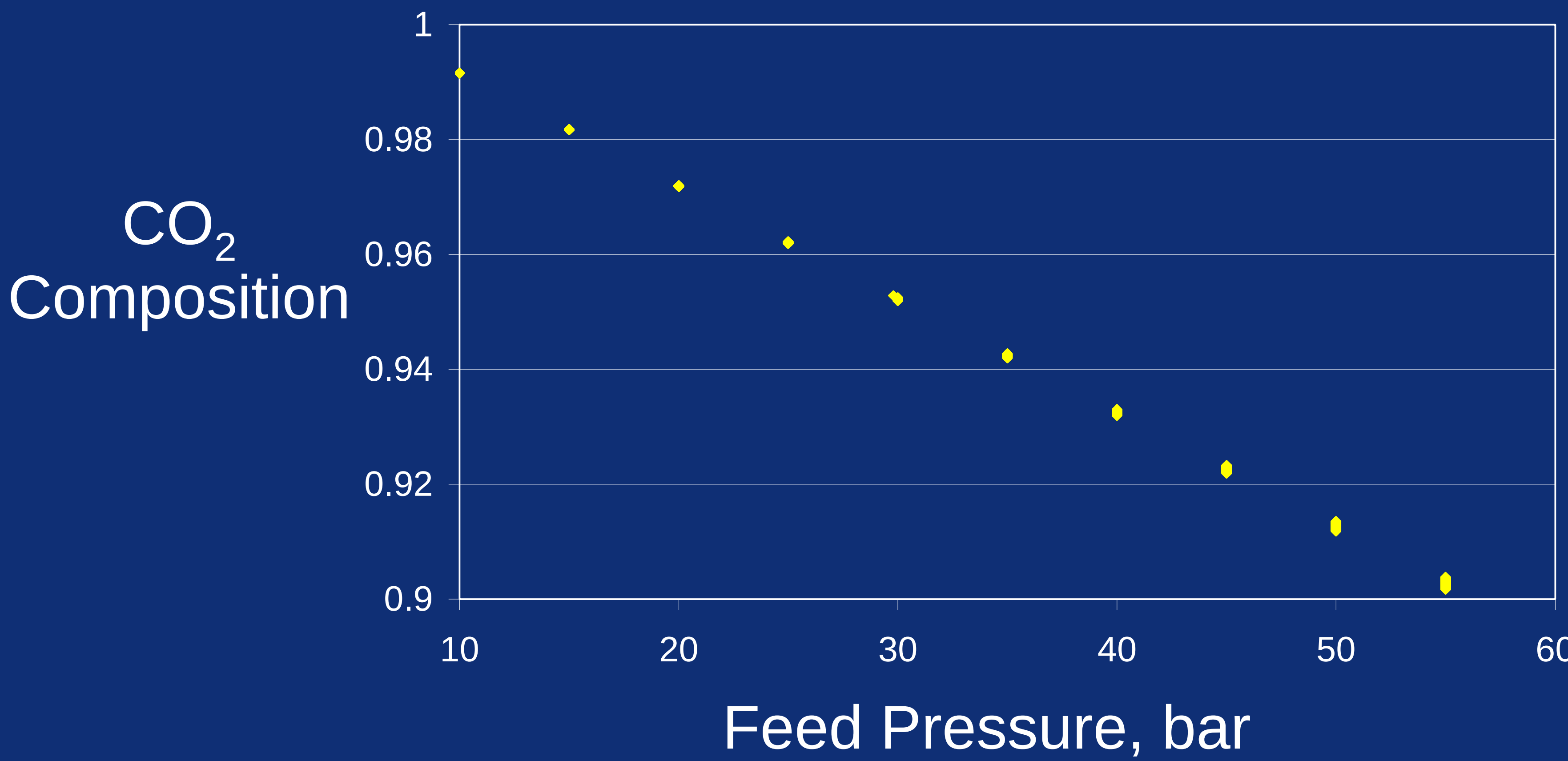
Purification of Oxyfuel-Derived CO_2 for Sequestration or EOR

- CO_2 produced from oxyfuel requires purification
  - Cooling to remove water
  - Inerts removal
  - Compression
- Current design has limitations
  - SOx/NOx removal
  - Oxygen removal
  - Recovery limited by phase separation
- New concepts for purification have been developed (since the IEA GHG Oxyfuel report)

CO_2 Compression and Purification System – Inerts removal and compression to 110 bar



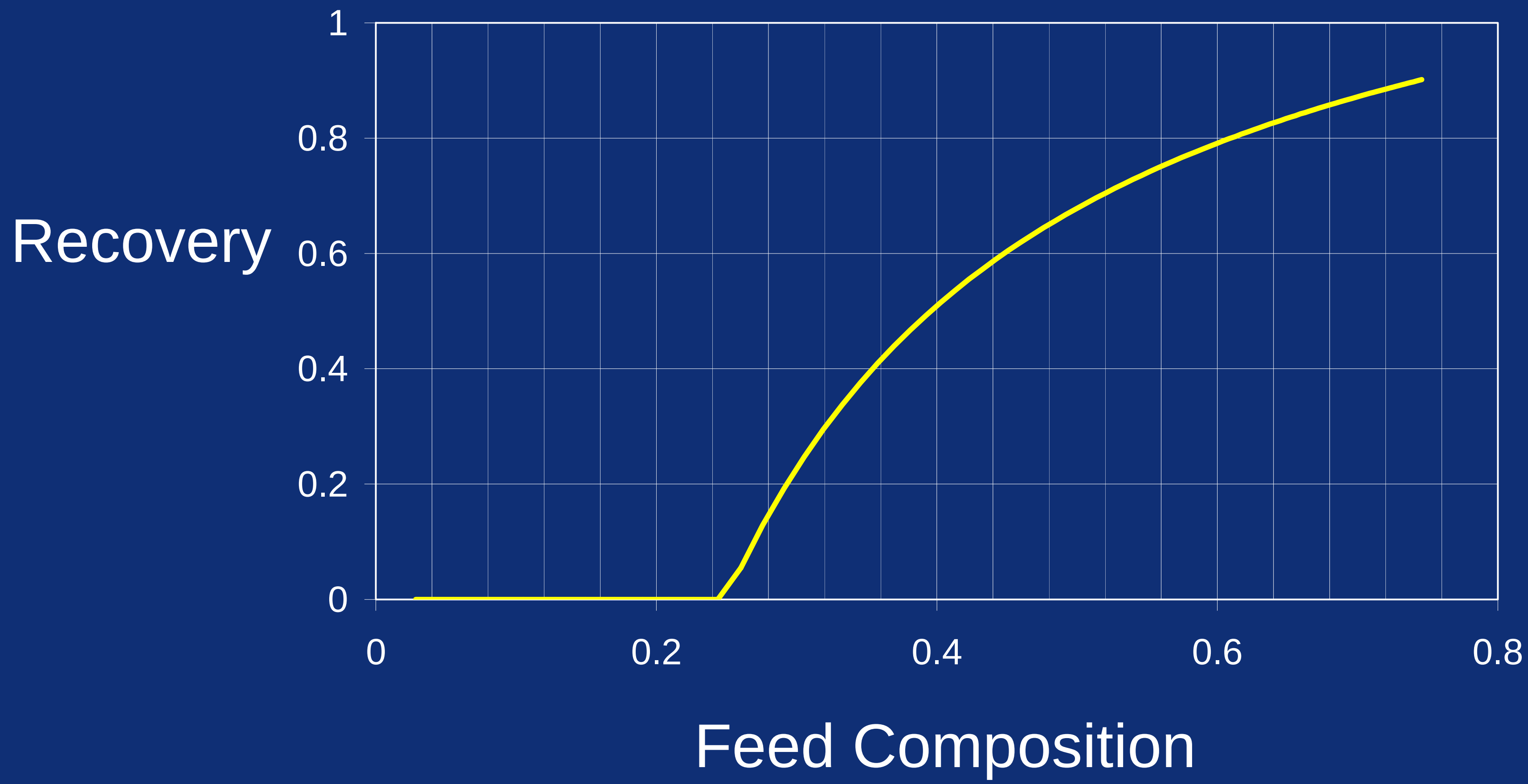
CO_2 Purity Depends On Feed Pressure



At -55°C

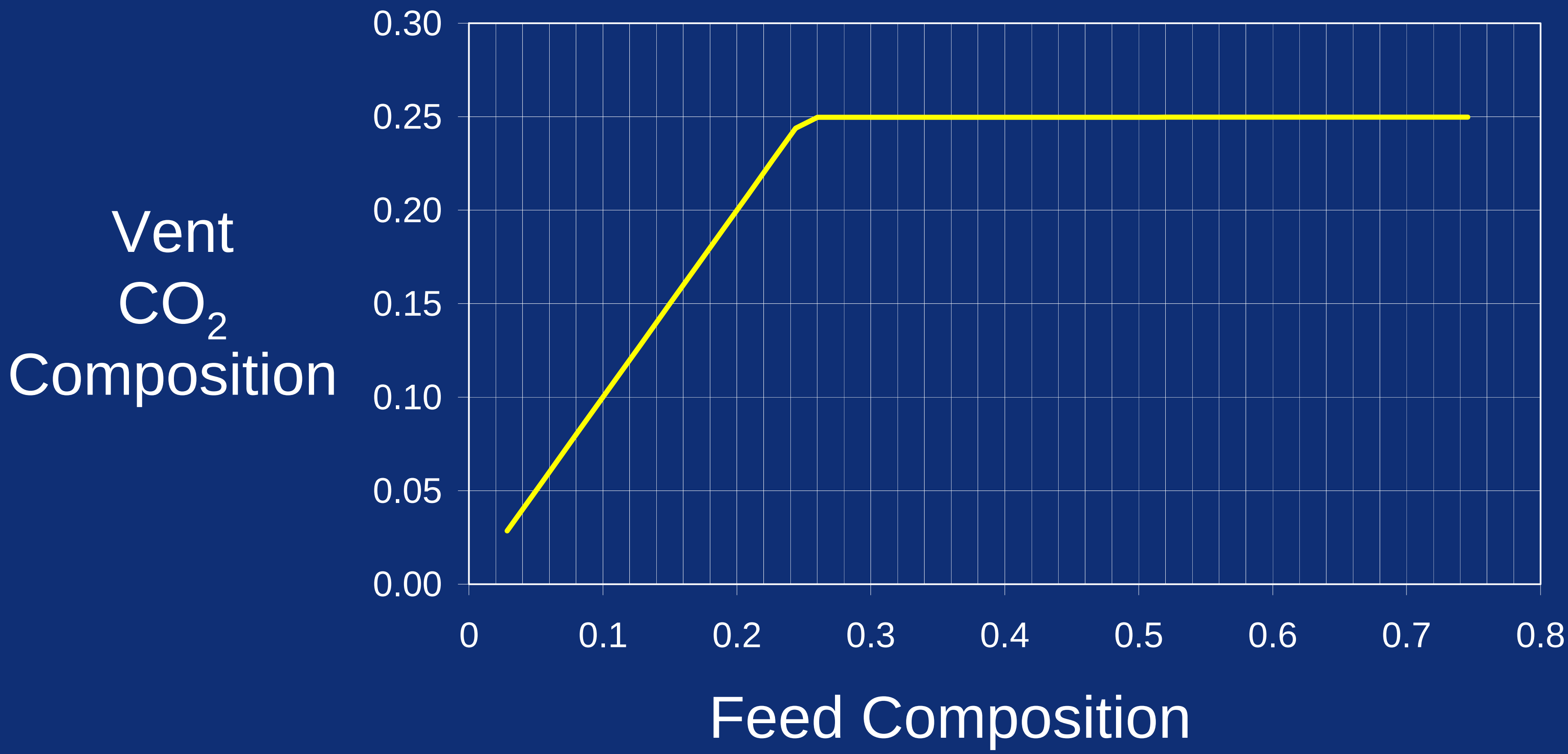
AIR PRODUCTS

CO_2 Recovery Depends On Feed Composition



At -55°C, 30 bar

CO_2 Recovery Depends On Feed Composition



At -55°C, 30 bar

CO_2 Purity and Recovery

- -55°C is as cold as we can make the phase separation
- CO_2 purity depends on pressure
  - At 30 bar and -55°C, CO_2 purity is 95%
  - Higher pressure gives lower purity CO_2
- CO_2 recovery depends on pressure
  - Lower pressure gives lower CO_2 recovery
  - At 15 bar and -55°C, CO_2 recovery is 75%
  - At 30 bar and -55°C, CO_2 recovery is 90%
- CO_2 recovery depends on feed composition
  - Increases from zero at 25mol% to 90% at 75mol%
  - Reducing air ingress increases CO_2 capture rate

Raw and Product CO_2 Compositions

	Raw Flue Gas @ 35°C, 1.02 bara mol%	CO_2 Product @ 35°C, 110 bar mol% Prior Art	Vent @ 11°C, 1.1 bar mol% Prior Art
CO_2	71.5	95.8	24.6
N_2	14.3	2.0	48.7
O_2	5.9	1.1	19.4
Ar	2.3	0.6	7.1
SO_2	0.4	0.5	0
NO	400 ppm	13 ppm	1180 ppm
NO_2	10 ppm	0	0
H_2O	5.6	0	0

AIR PRODUCTS

CO_2 Purity Issues

	Basic Design Case	EOR Case
H_2O	< 500 ppm	< 50 ppm
CO_2	> 90% mol	> 90% mol
SO_2	From H&MB	< 50 ppm
NO	From H&MB	From H&MB
O_2	< 4% mol	100 ppm
Ar + N_2 + O_2	< 4% mol	< 4% mol

- **Regulations regarding onshore and off-shore disposal are being drafted world-wide**
- **Co-disposal of other wastes (NOx, SOx, Hg) is a sensitive issue**
- **Important that the CO_2 can be purified for disposal or EOR**

AIR PRODUCTS

NOx SO_2 Reactions in the CO_2 Compression System

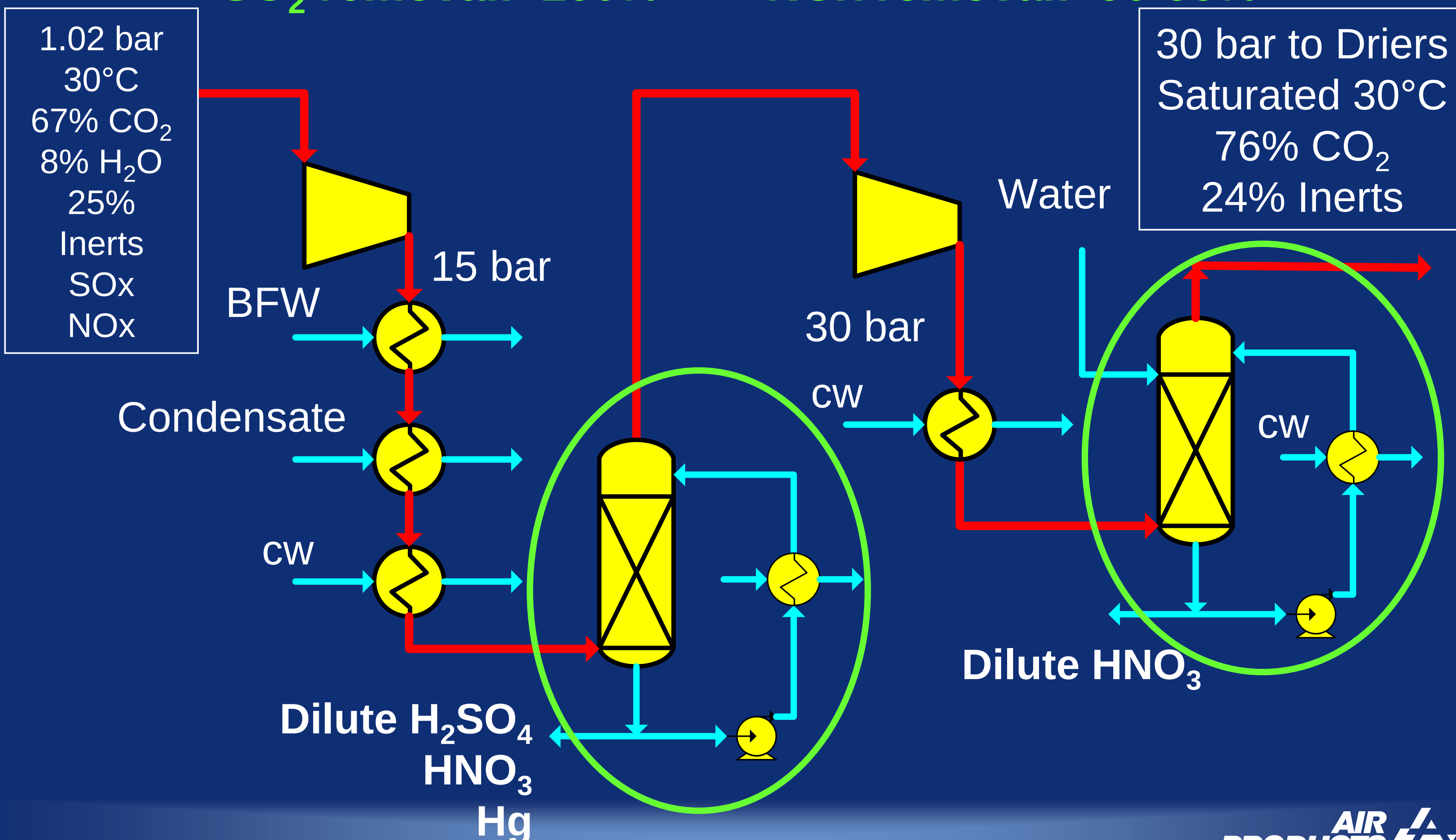
- **We realised that SO_2, NOx and Hg can be removed in the CO_2 compression process, in the presence of water and oxygen.**
- **SO_2 is converted to Sulphuric Acid, NO_2 converted to Nitric Acid:**

– $NO + ½ O_2$	=	NO_2	(1)	Slow
– $2 NO_2$	=	N_2O_4	(2)	Fast
– $2 NO_2 + H_2O$	=	$HNO_2 + HNO_3$	(3)	Slow
– $3 HNO_2$	=	$HNO_3 + 2 NO + H_2O$	(4)	Fast
– $NO_2 + SO_2$	=	$NO + SO_3$	(5)	Fast
– $SO_3 + H_2O$	=	H_2SO_4	(6)	Fast

- **Rate increases with Pressure to the 3rd power**
  - **only feasible at elevated pressure**
- **No Nitric Acid is formed until all the SO_2 is converted**
- **Pressure, reactor design and residence times, are important.**

CO_2 Compression and Purification System – Removal of SO_2, NOx and Hg

- **SO_2 removal: 100%   NOx removal: 90-99%**



AIR PRODUCTS

SOx/NOx Removal – Key Features

- **Adiabatic compression to 15 bar:**
  - **No interstage water removal**
  - **All Water and SOx removed at one place**
- **NO acts as a catalyst**
  - **NO is oxidised to NO_2 and then NO_2 oxidises SO_2 to SO_3: The Lead Chamber Process**
- **Hg will also be removed, reacting with the nitric acid that is formed**

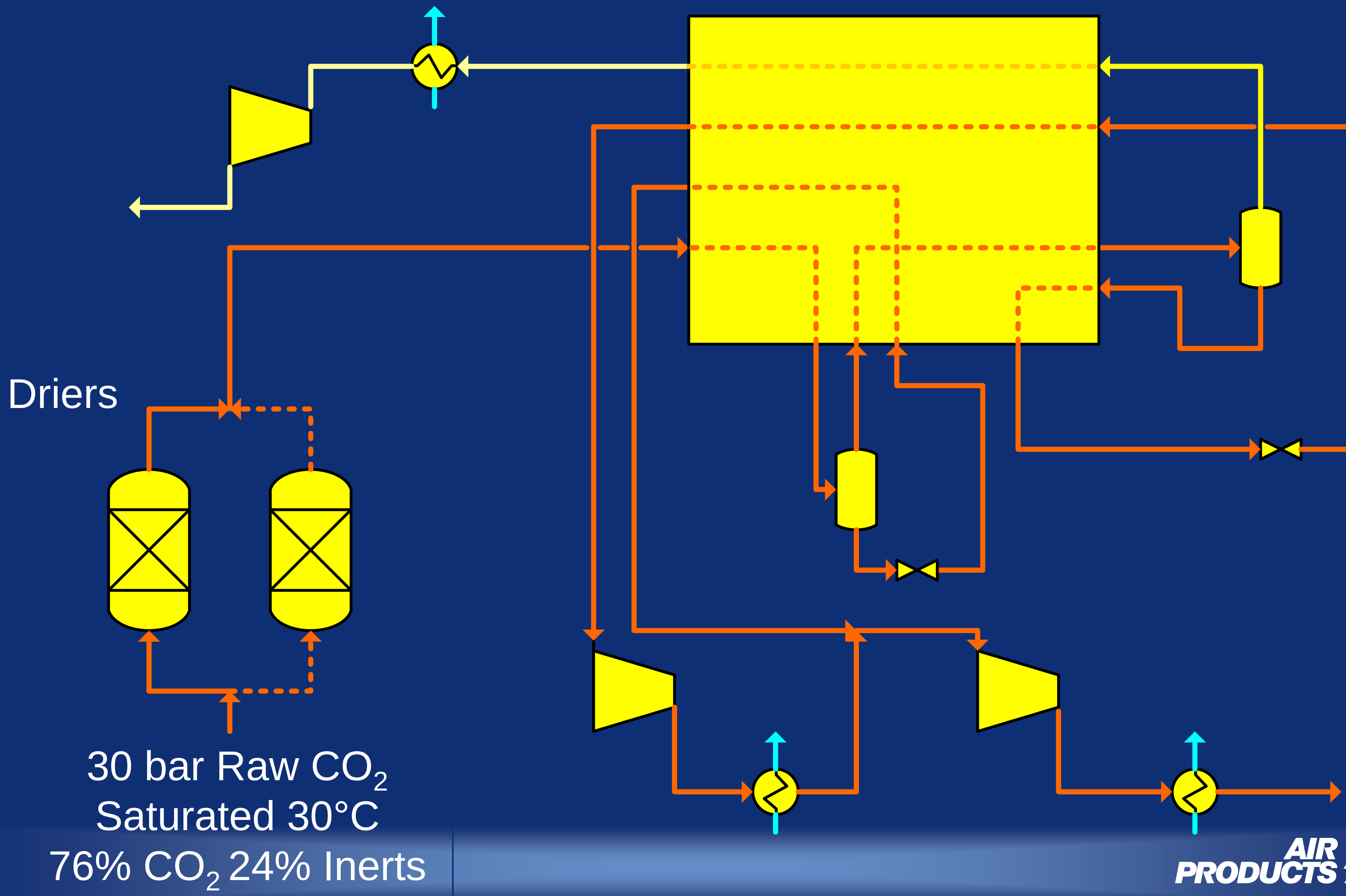
AIR PRODUCTS

Corrected CO_2 Purity

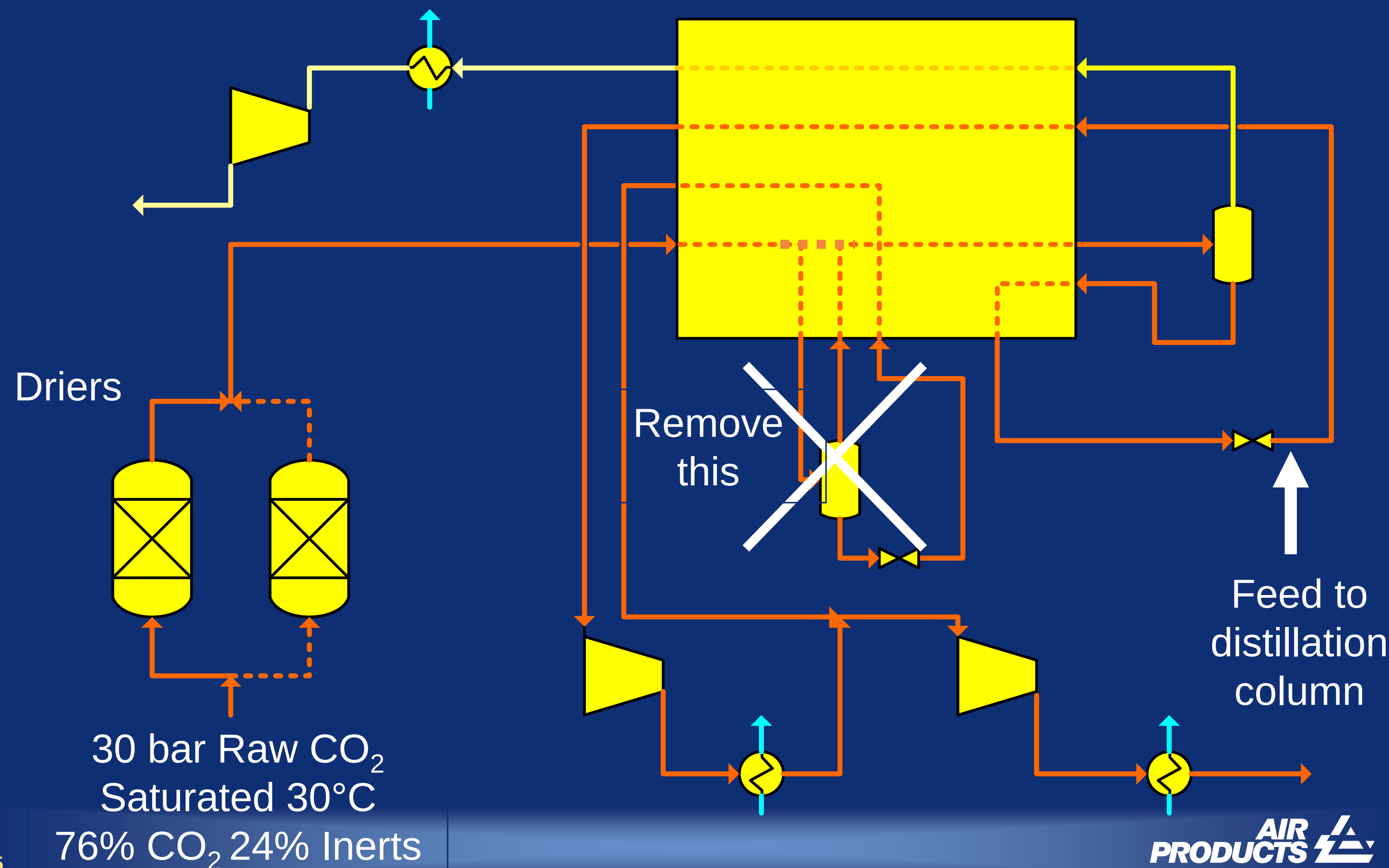
	Raw Flue Gas @ 35°C, 1.02 bara mol%	CO_2 Product @ 35°C, 110 bar mol% Prior Art	Vent @ 11°C, 1.1 bar mol% Prior Art	CO_2 Product @ 35°C, 110 bar mol% Corrected	Vent @ 11°C, 1.1 bar mol% Corrected
CO_2	71.5	95.8	24.6	96.3	24.6
N_2	14.3	2.0	48.7	2.0	48.7
O_2	5.9	1.1	19.4	1.1	19.4
Ar	2.3	0.6	7.1	0.6	7.1
SO_2	0.4	0.5	0	0	0
NO	400 ppm	13 ppm	1180 ppm	< 10 ppm	< 100 ppm
NO_2	10 ppm	0	0	< 10 ppm	0
H_2O	5.6	0	0	0	0

And Oxygen removal from the CO_2?

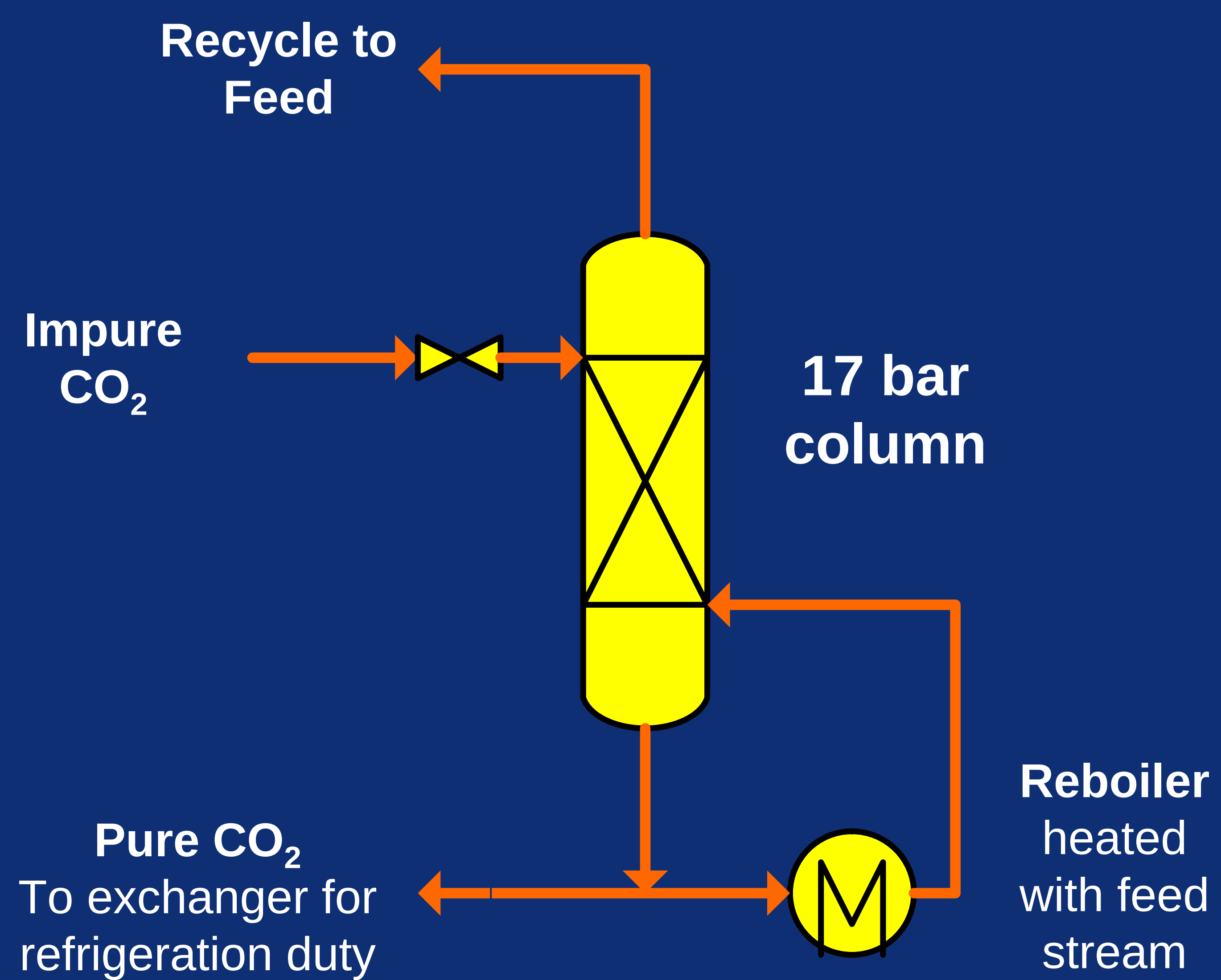
Where does the distillation column go?



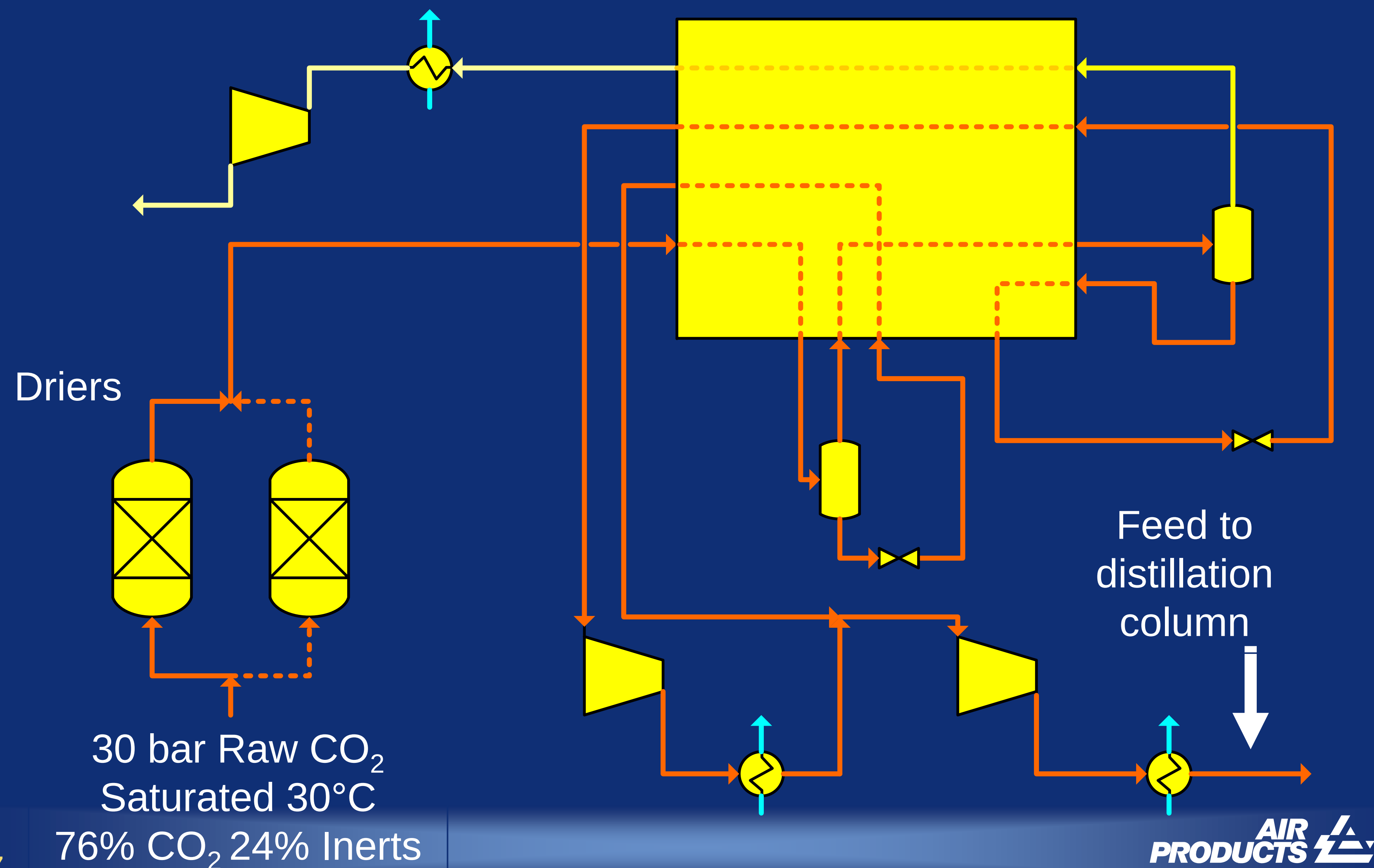
Oxygen removal – Option 1



Oxygen removal – Option 1

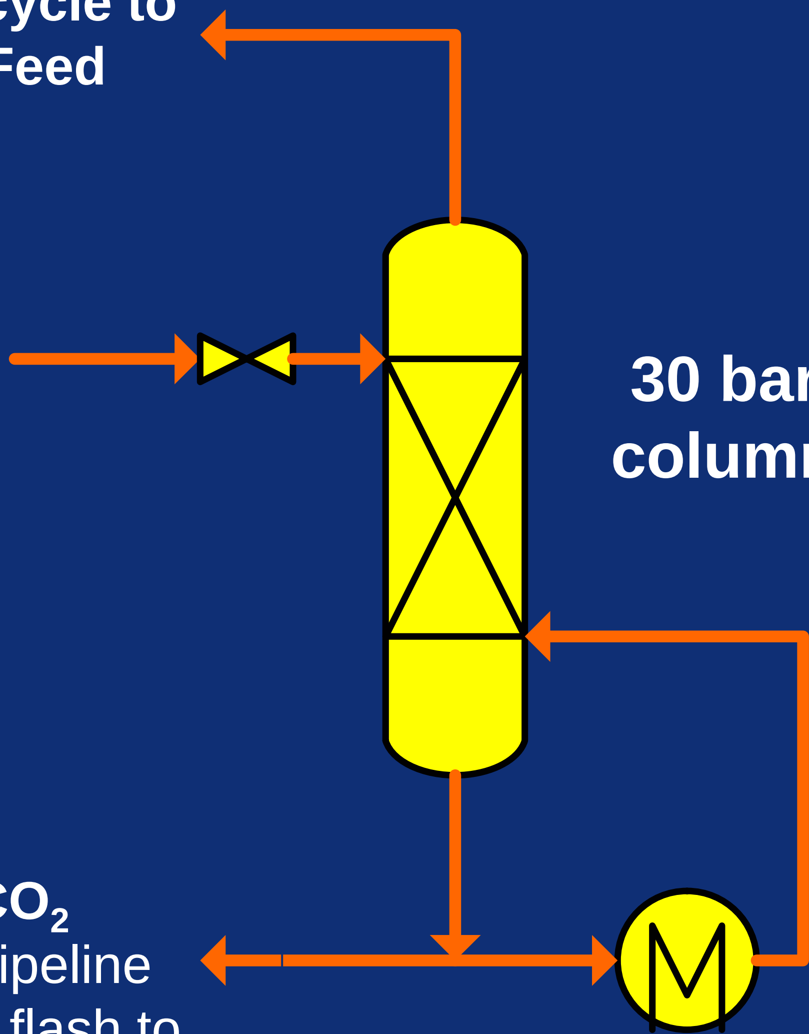


Oxygen removal – Option 2



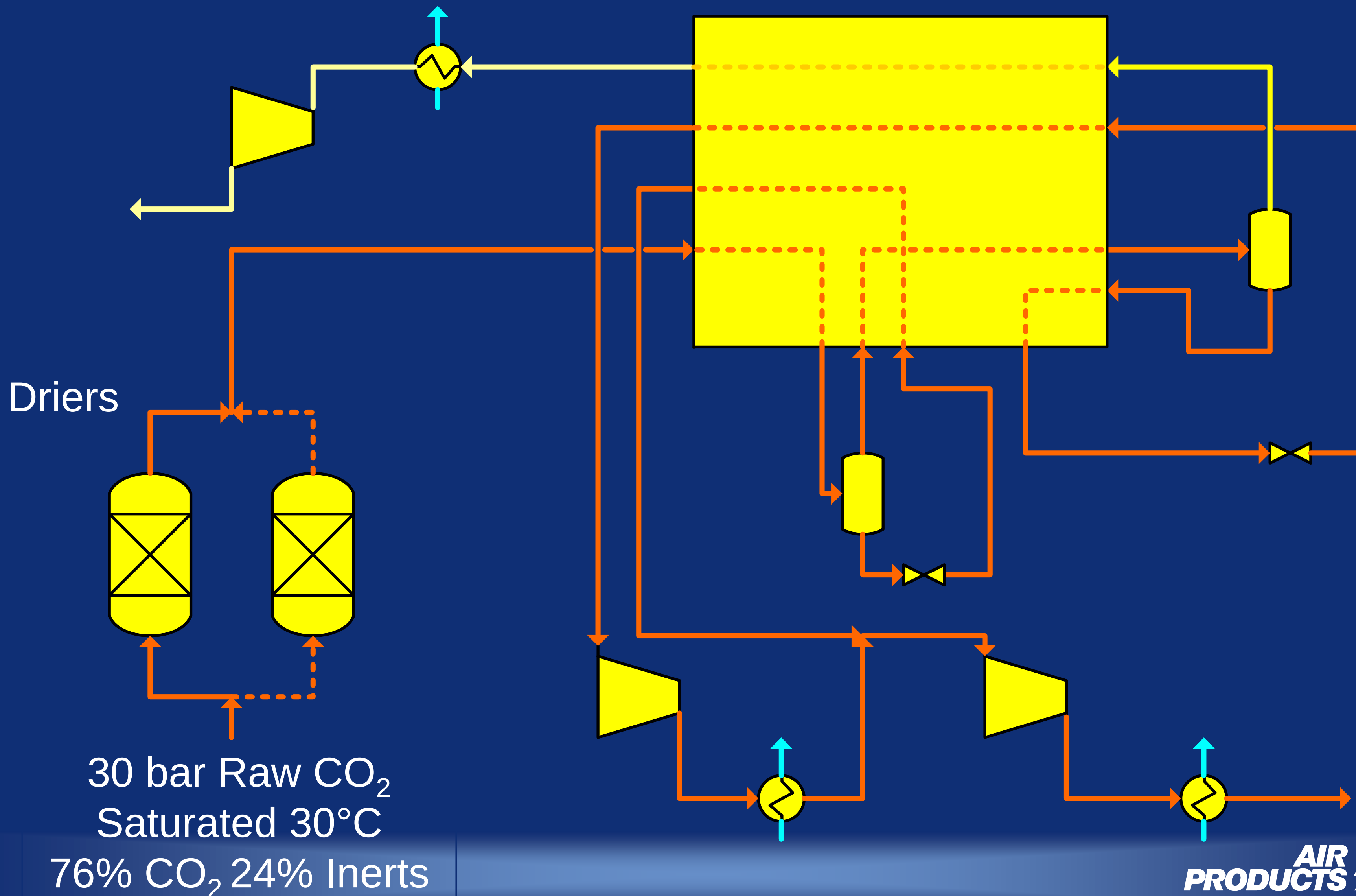
AIR PRODUCTS

Oxygen removal – Option 2

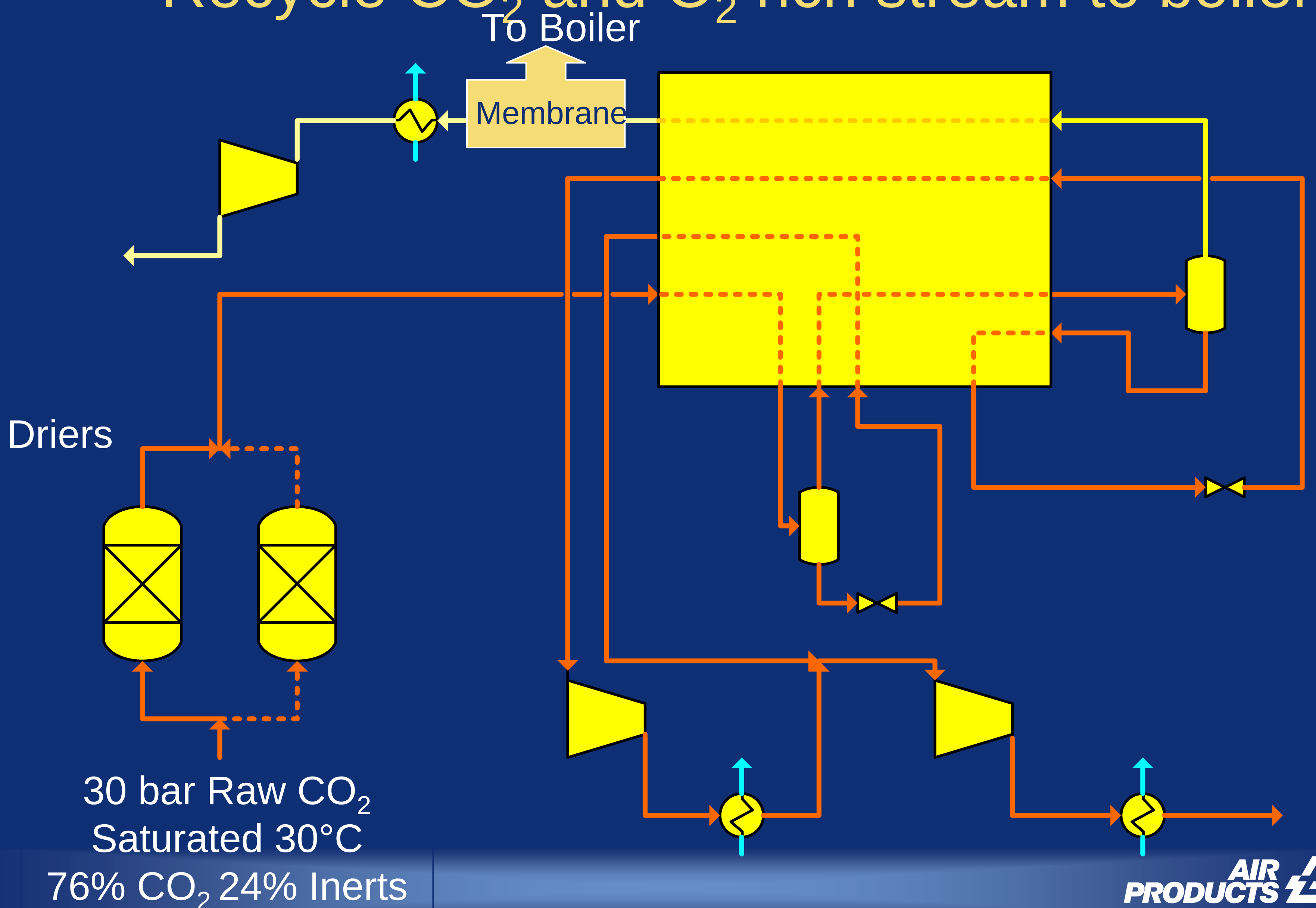


Can we improve on 89% CO_2 Capture?

Vent stream is at pressure and is CO_2 (and O_2) rich



Put membrane in vent stream
Recycle CO_2 and O_2 rich stream to boiler



AIR PRODUCTS

Purity, Recovery and Power

- **Power includes ASU and CO_2 system power**

Description	CO_2 Purity	Oxygen Content	CO_2 Pressure	CO_2 Recovery	Relative Specific Power
Standard Cycle	95.90 mol%	0.91 mol%	110 bar	89.0%	1.00
High Purity Option 1	99.89 mol%	100.00 ppm	110 bar	87.4%	1.03
High Purity Option 2	99.98 mol%	100.00 ppm	110 bar	87.7%	0.99
30 bar liquid CO_2	99.98 mol%	100.00 ppm	30 bar	87.7%	0.98
7 bar liquid CO_2	100.00 mol%	5.01 ppm	7 bar	87.7%	1.02
Standard with membrane	96.30 mol%	0.73 mol%	110 bar	97.7%	0.91
High purity Option 1 with membrane	99.86 mol%	100.00 ppm	110 bar	97.9%	0.97

Conclusions

- FGD and DeNOx systems are not required to meet tight CO_2 purity specifications
  - Co-disposal of SO_2 with CO_2 is not possible
  - Compressing CO_2 with NO + SO_2 + O_2 + Water will result in H_2SO_4 production
  - Low NOx burners are not required for oxyfuel combustion
- Oxygen can be removed for EOR-grade CO_2
- No penalty if liquid CO_2 is required
- Capture of CO_2 increased to 98% with CO_2 membrane
  - Also reduces ASU size (~5% reduction)

Thank you

tell me more

www.airproducts.com

IEAGHG International OxyCombustion Network

2nd Workshop

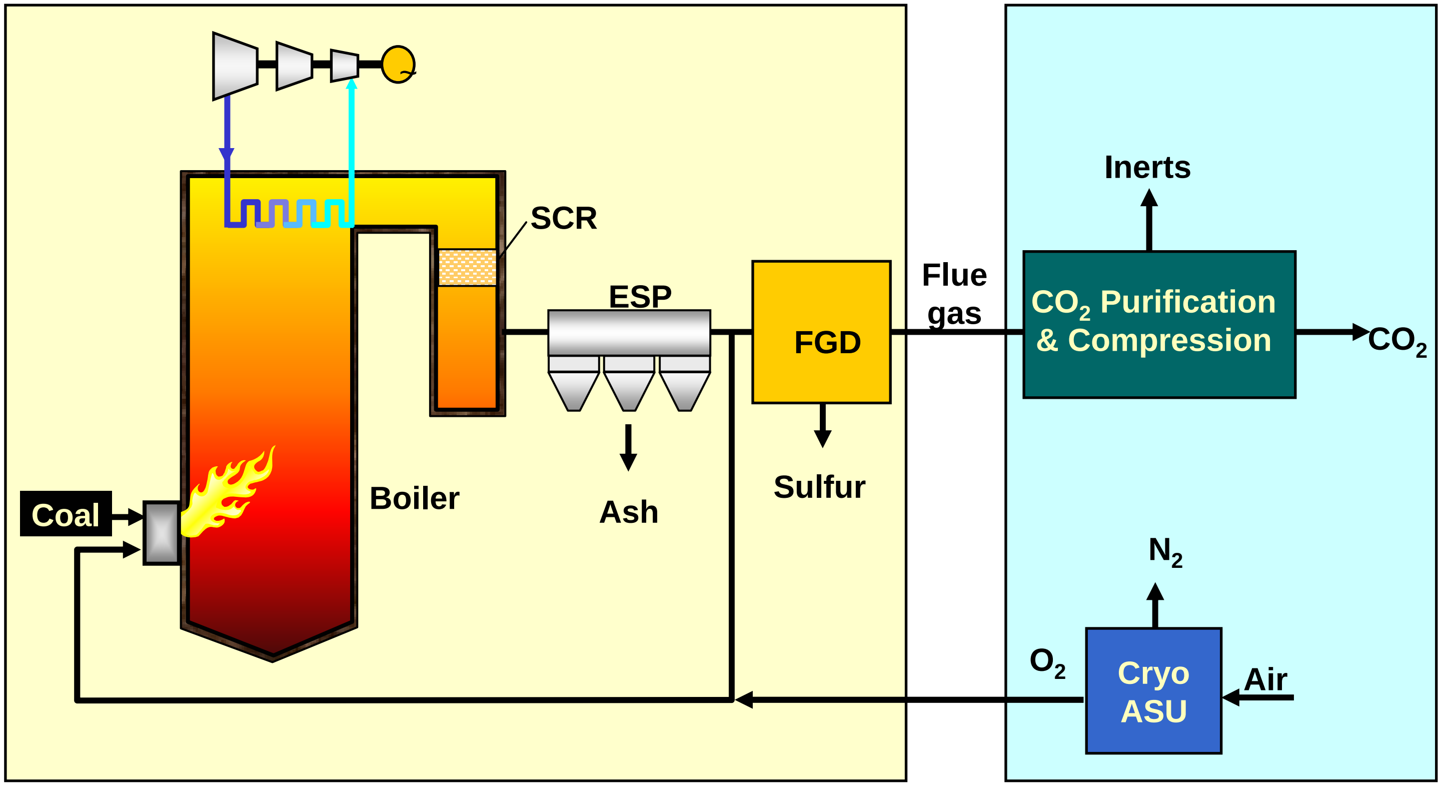
Oxy-Fuel Combustion Using OTM For CO_2 Capture from Coal Power Plants

Minish M. Shah and Maxwell Christie

PRAXAIR

January 25 - 26, 2007 • Windsor, CT, USA

Conventional Oxy-Fuel Process



- Oxygen supplied from cryogenic ASU
- Flue gas recirculation for temperature control
- 3% O_2 in wet flue gas
- Suitable for retrofit and CO_2 capture ready designs

Need for New Oxy-Fuel Technology

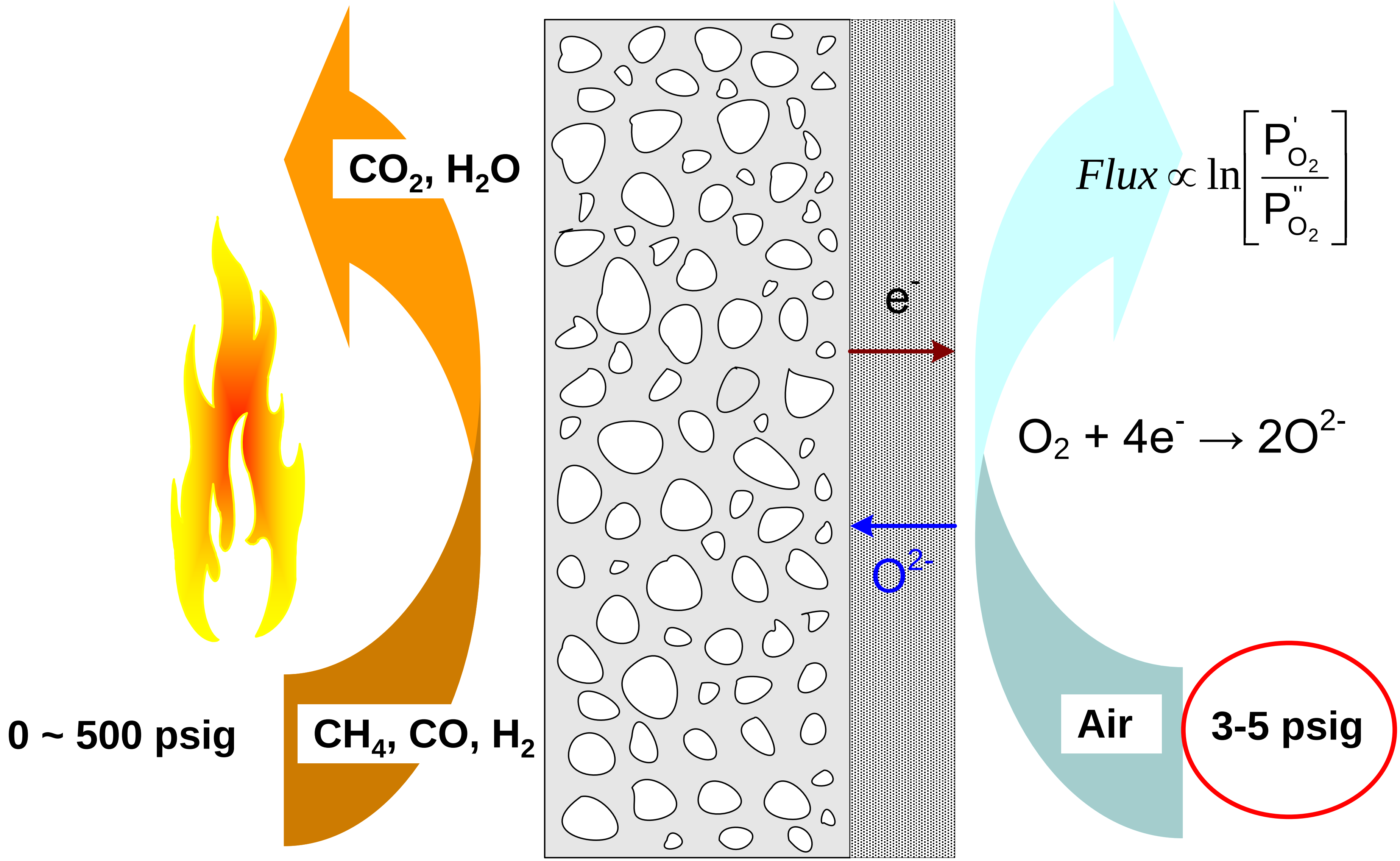
PRAXAIR

- **Conventional oxy-fuel process (cryogenic ASU) will have a large energy penalty for capturing CO_2**
  - 15 – 20% of power output is consumed by cryogenic ASU
  - ~10% for compressing and purifying CO_2
- **Cryogenic ASU technology is mature**
  - Improvements likely to be incremental
- **Need for a technology that makes a step-change improvement in efficiency**

Oxygen Transport Membrane (OTM)

"Electrochemical Filter and Pump"

PRAXAIR



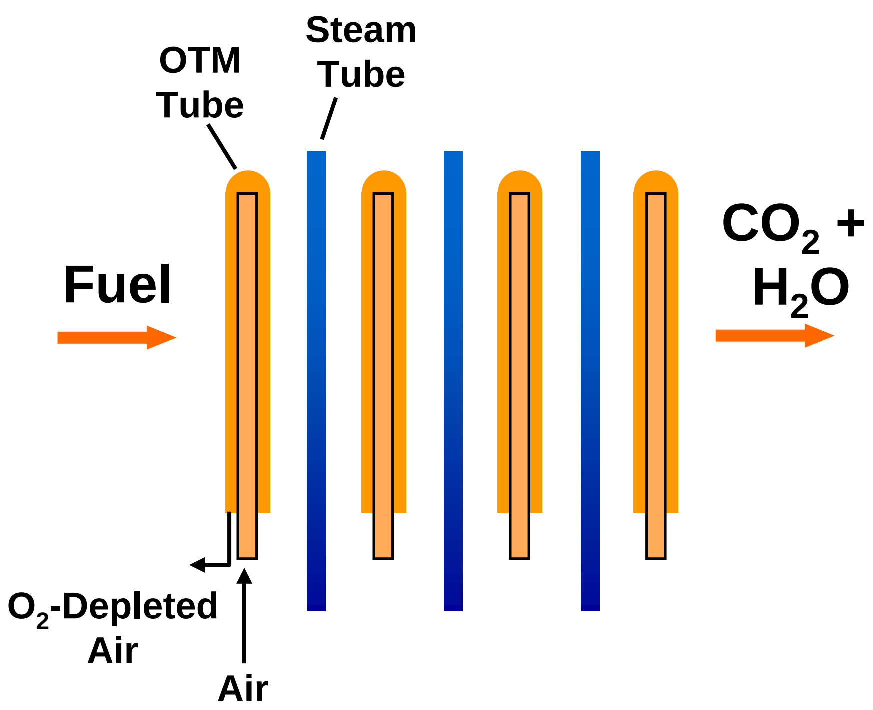
Oxy-Fuel Combustion Without Producing Oxygen

Advanced Boiler Concept

PRAXAIR

Patents

- **US 6,394,043**
- **US 6,562,104**

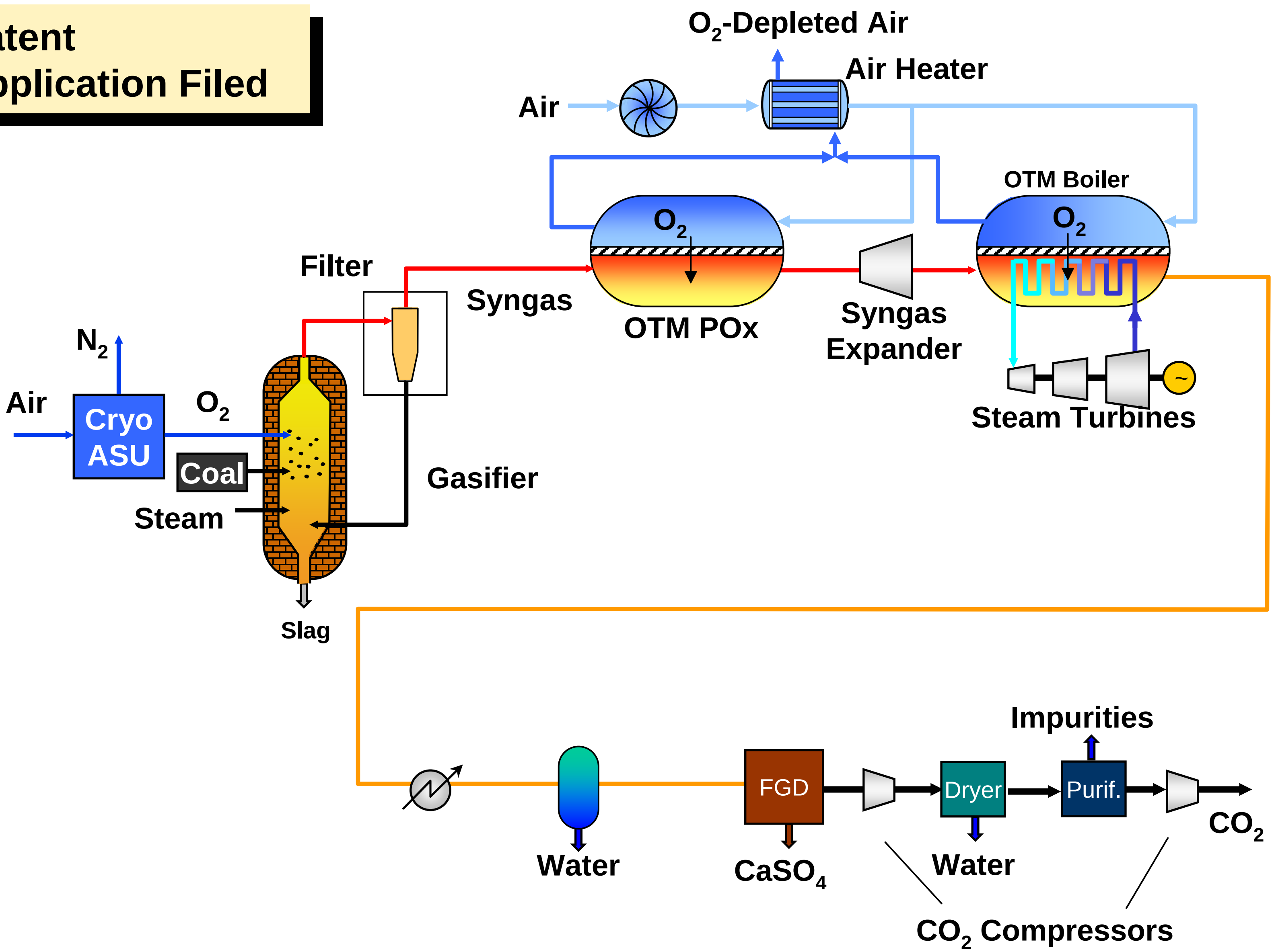


- Array of OTM tubes interspersed with steam tubes
- Alternating heat source and sink will maintain temperature profile
- Flue gas recirculation not needed
- CO_2 concentration could be 85 to 95% (dry basis) depending on the air leak and excess O_2 content

Process Scheme

PRAXAIR

Patent Application Filed



Technology Features

PRAXAIR

- Potential to achieve up to 100% CO_2 capture
- OTM oxygen separation power reduced by > 70% compared to a cryogenic process
- Power generation efficiency up by > 4% points compared to a conventional oxy-fuel process
- Low NOx emissions without using SCR

Comparison

PRAXAIR

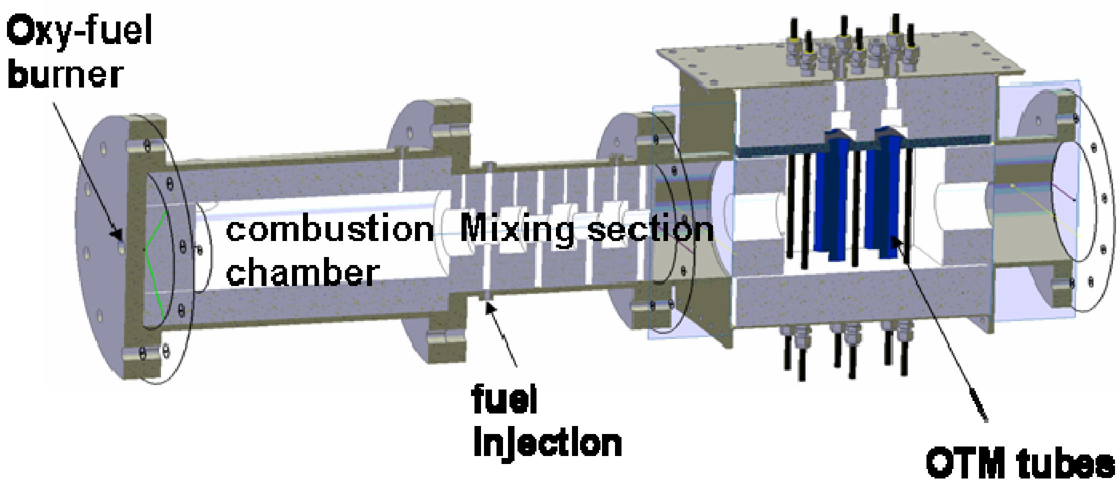
	Air Fired PC Boiler	Oxy-PC w/ CO_2 Capture	OTM Process w/ CO_2 Capture
Net Output, MW	600	600	600
Efficiency % HHV	39.1%	29.9%	34.5%
CO_2 Emissions, t/MWh	0.88	0.12	0.016
Purity of Captured CO_2, %	-	96%	96%
% CO_2 Captured	-	90%	98.4%
% CO_2 Avoided	-	86%	98.2%

Technology Capabilities

- **Facilities**
  - Powder production in Woodinville, WA
  - OTM tube fabrication in Indianapolis, IN
  - Lab and pilot plant facilities in Tonawanda, NY
- **10+ yrs experience in ceramic membrane technology**
  - Fundamental understanding of OTM materials science
  - CIP tube manufacturing technology for >5-ft long composite tubes
  - Bench/pilot scale test infrastructure
  - Process integration and economic assessment
- **Strong patent portfolio**
  - Materials
  - Reactors
  - Processes

Technology Status
Oxy-Combustion

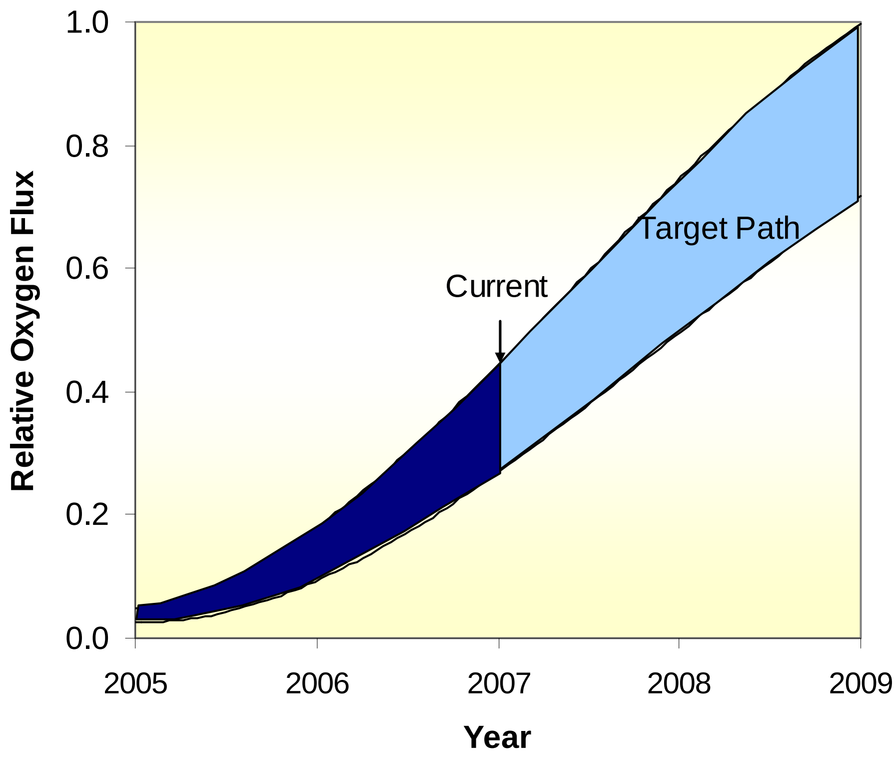
- **Robust materials**
  - 20,000 hrs cumulative testing of single tubes, no failures (Ambient pressure)
  - Multiple thermal & chemical cycles
- **Demonstrated in multi-tube reactor**
  - Dry flue gas 90-95% CO_2, ~1%O_2, balance N_2 from air-leak and NG, (25ppm CO)



Technology Status
Oxy-Combustion

PRAXAIR

- **Oxygen Transport Rates**
  - Significant progress over last two years
  - Further 2x – 5x improvement needed
  - Installed OTM cost and process integration will dictate the target

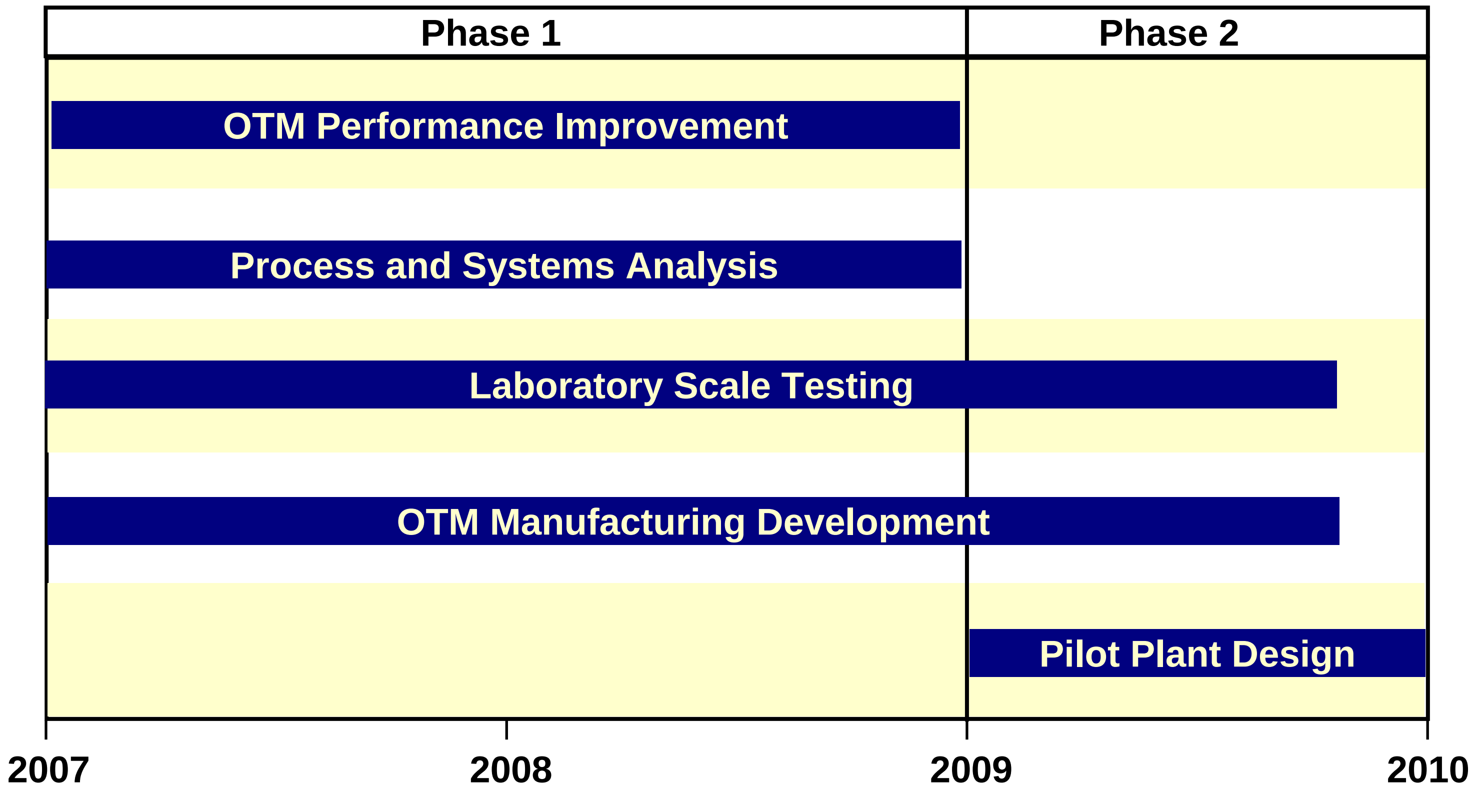


Challenges

PRAXAIR

- **Achieving high oxygen flux through OTM whilst maintaining reliability**
- **Technical feasibility of combusting coal-derived syngas using OTM**
  - Interaction with coal impurities
  - Tolerance to sulfur compounds
  - Understand extent of cleanup required before exposing OTM to syngas
  - Proposal to work with University of Utah Center for Clean Coal Technology
- **Longer term**
  - Manufacturing infrastructure for OTM
  - Design and engineering of a large scale OTM boiler
  - Gasifier and boiler costs

Technology Roadmap 2007 - 2009



Summary

PRAXAIR

- Robust membranes developed
- Demonstrated combustion of NG in a multi-tube reactor
- Developed process concept for integration with coal-based power plant
- Efficiency of power plant with CO_2 capture will improve by > 4% points compared to a conventional oxy-fuel process
- Focus of the next phase will be on flux improvement and optimizing process scheme

Acknowledgements

PRAXAIR

Parts of this presentation were written with support of the U.S. Department of Energy under Contract No. DE-FC26-01NT41147. The Government reserves for itself and others acting on its behalf a royalty-free, nonexclusive, irrevocable, worldwide license for Governmental purposes to publish, distribute, translate, duplicate, exhibit and perform this copyrighted presentation.

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

NETL

PRAXAIR

Oxygen Production Technologies: Cryogenic and ITM

Phil Armstrong, Kevin Fogash
Air Products and Chemicals, Inc.
Allentown, Pennsylvania

2nd IEAGHG International Oxy-Combustion Network Workshop
Windsor, CT, USA
25-26 January 2007

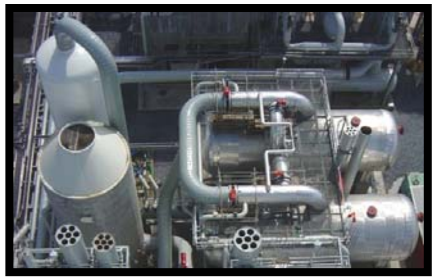
Air Separation

- **Cryogenic air separation includes these major steps:**
  - **Compressing air**
  - **Air impurity removal (Pretreatment)**
  - **Cooling/liquefying air**
  - **Distillation**
- **Scale up of advanced oxygen production technology – ITM Oxygen**

The ASU Process

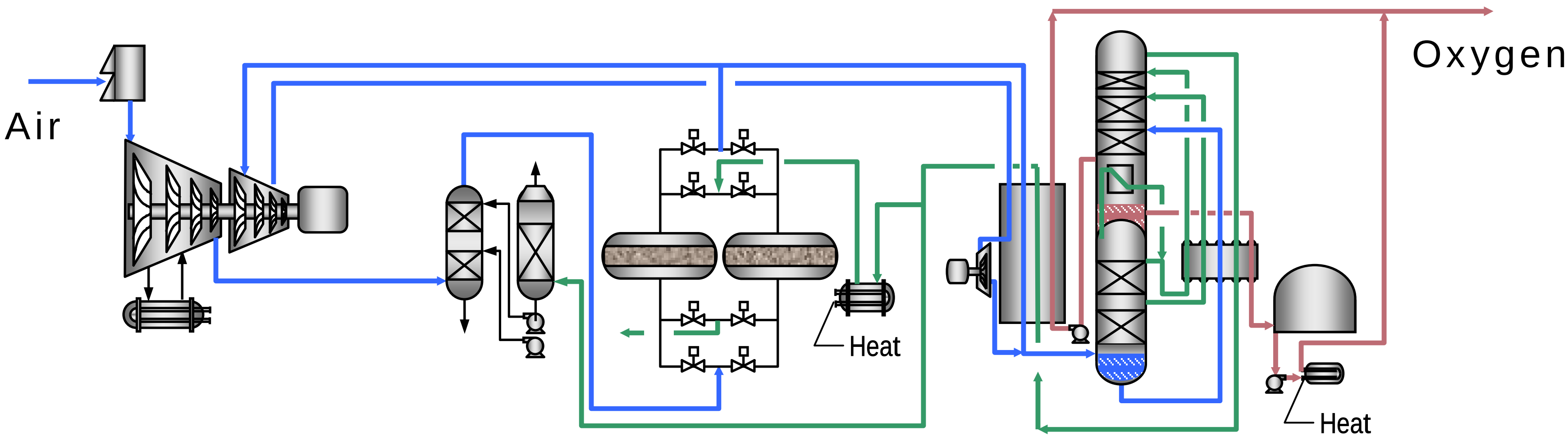
Main and Boost Air Compression

Air Cooling and Pretreatment



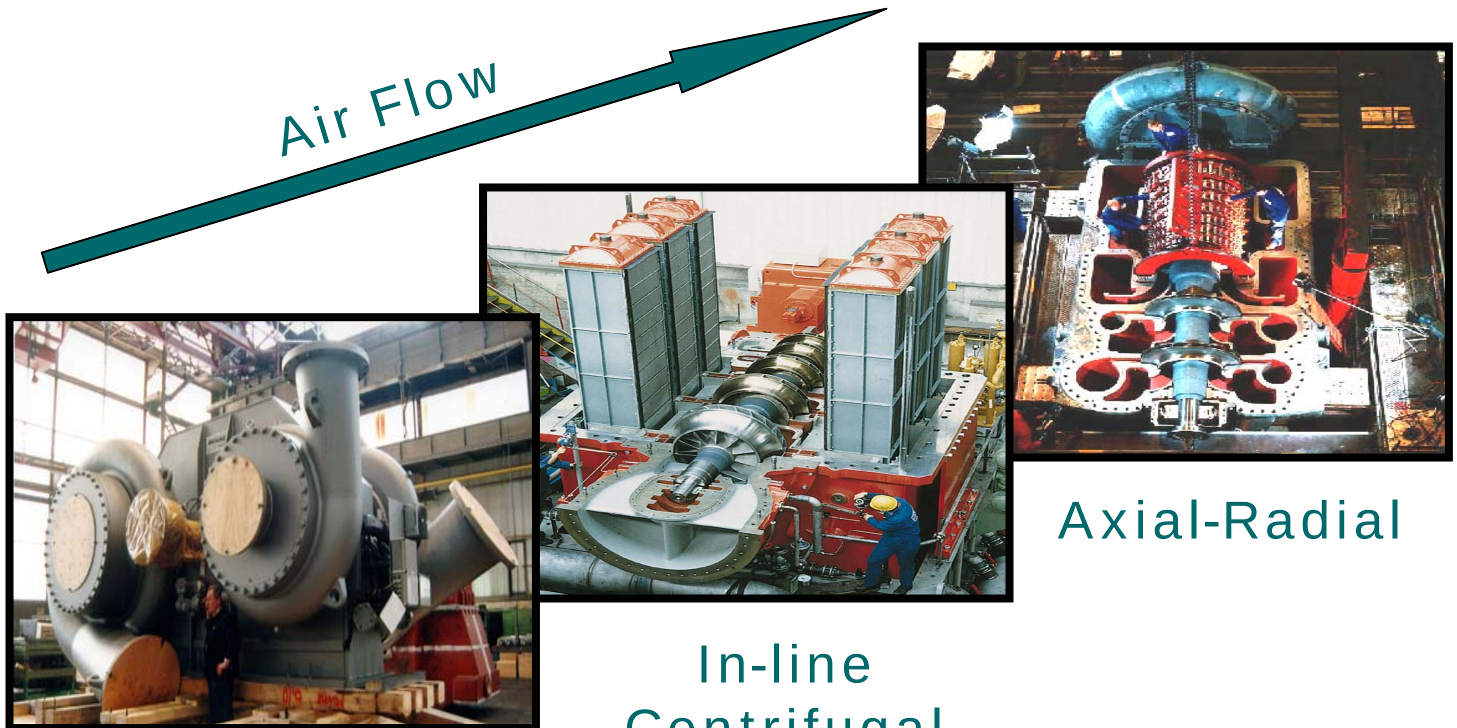
Cryogenic Separation

Storage



Main & Boost Air Compression

- Inlet air flow determines machine selection



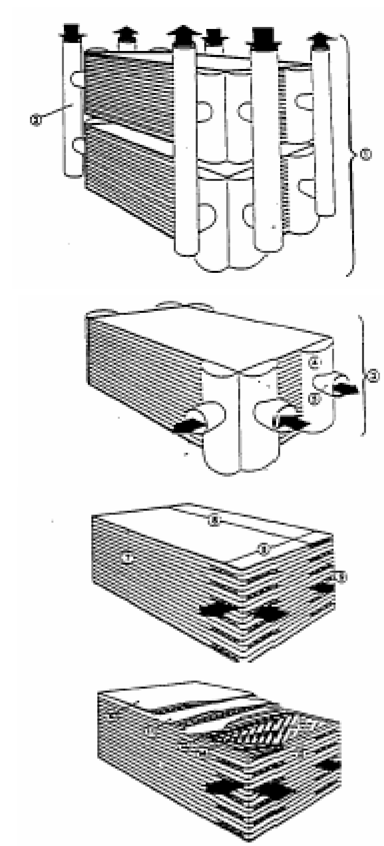
Integral Gear Centrifugal

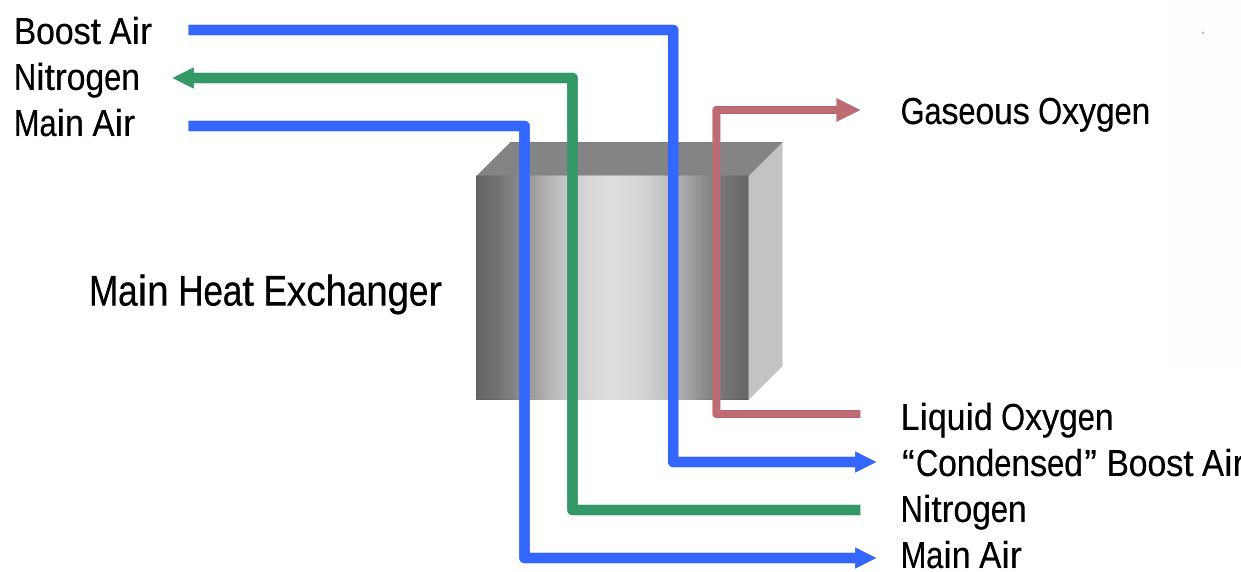
In-line Centrifugal

Axial-Radial

Cryogenic Heat Exchange

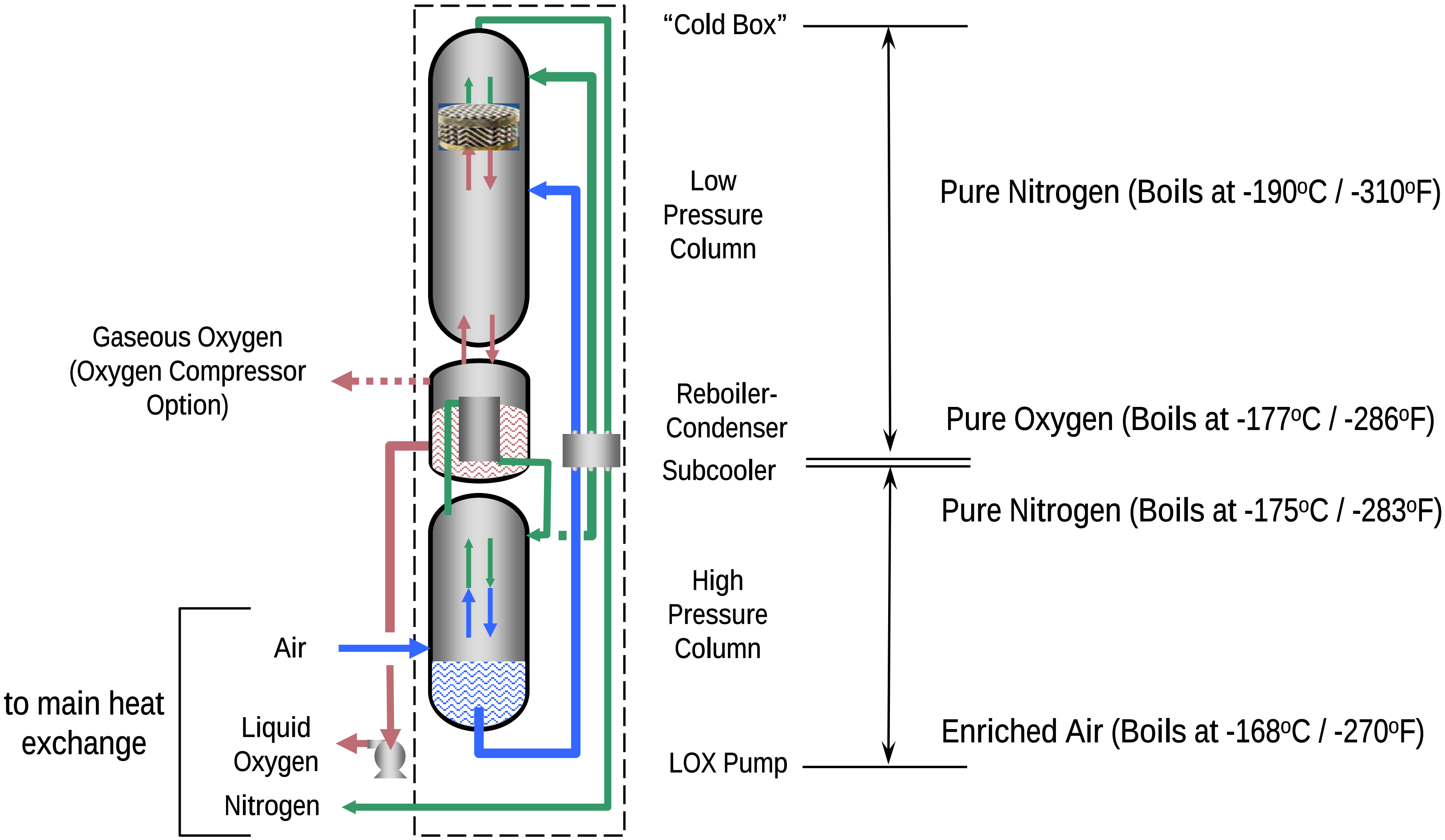
- Brazed aluminum plate fin exchangers
- Cools air streams against product streams to recover refrigeration
- Ambient to cryogenic temperatures





AIR PRODUCTS

Separation by Distillation



AIR PRODUCTS

Manufacturing

- **Manufacture/erection approach is project specific**

Shop manufactured distillation columns

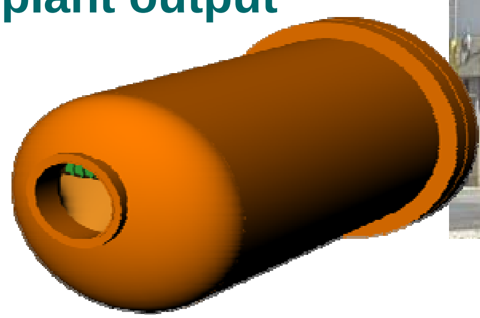
Shop manufactured cold boxes

Field erected column can

AIR PRODUCTS

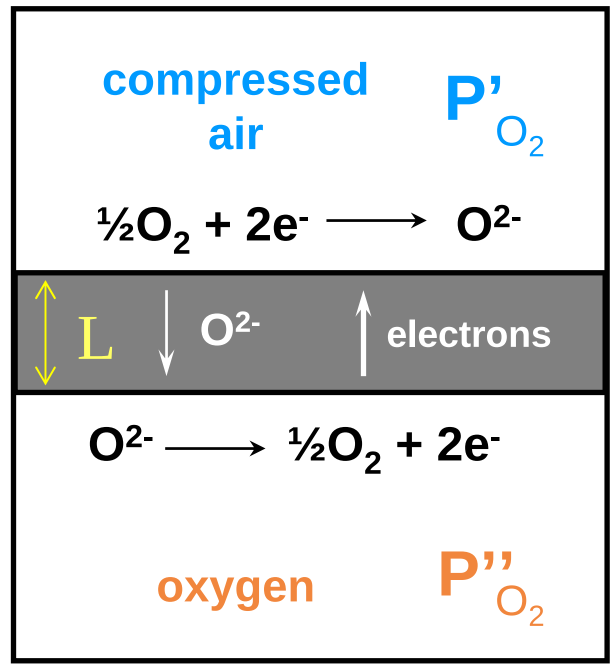
ITM Oxygen Enables a Step-change Reduction in the Cost of Oxygen

Conceptual ITM Oxygen vessel scaled to match cryogenic oxygen plant output

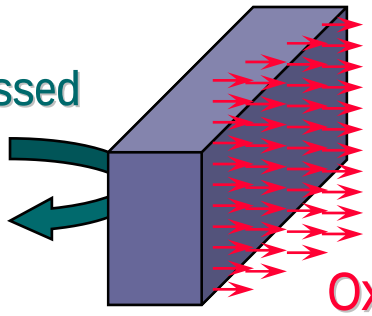


Ion Transport Membranes (ITM): High-flux, High-purity Oxygen

- **Mixed-conducting ceramic membranes (non-porous)**
- **Typically operate at 800-900 °C**
- **Crystalline structure incorporates oxygen ion vacancies**
- **Oxygen ions diffuse through vacancies**
- **100% selective for O_2**
- $O_2 Flux \propto \frac{1}{L}\ln\left(\frac{P'_{O2}}{P''_{O2}}\right)$



Ceramic Membranes: Revolutionary Technology for Tonnage Oxygen Supply

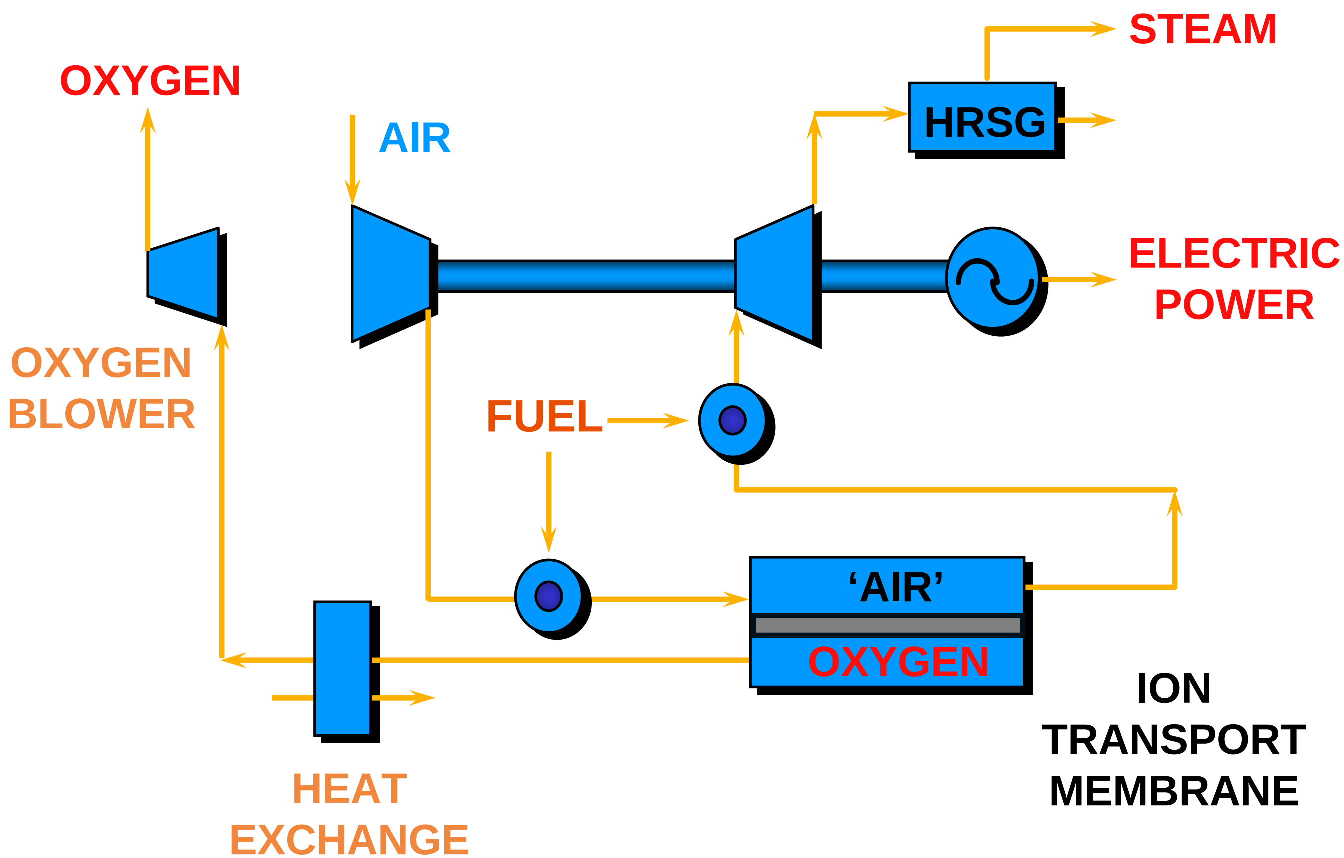


0.5 TPD module (commercial-scale)

- **Single-stage air separation leads to compact designs**
- **Low pressure drop on the high-pressure side**
- **High-temperature process has better synergy with power generation systems**
- **Extraordinary flux enables large tonnage production economics**

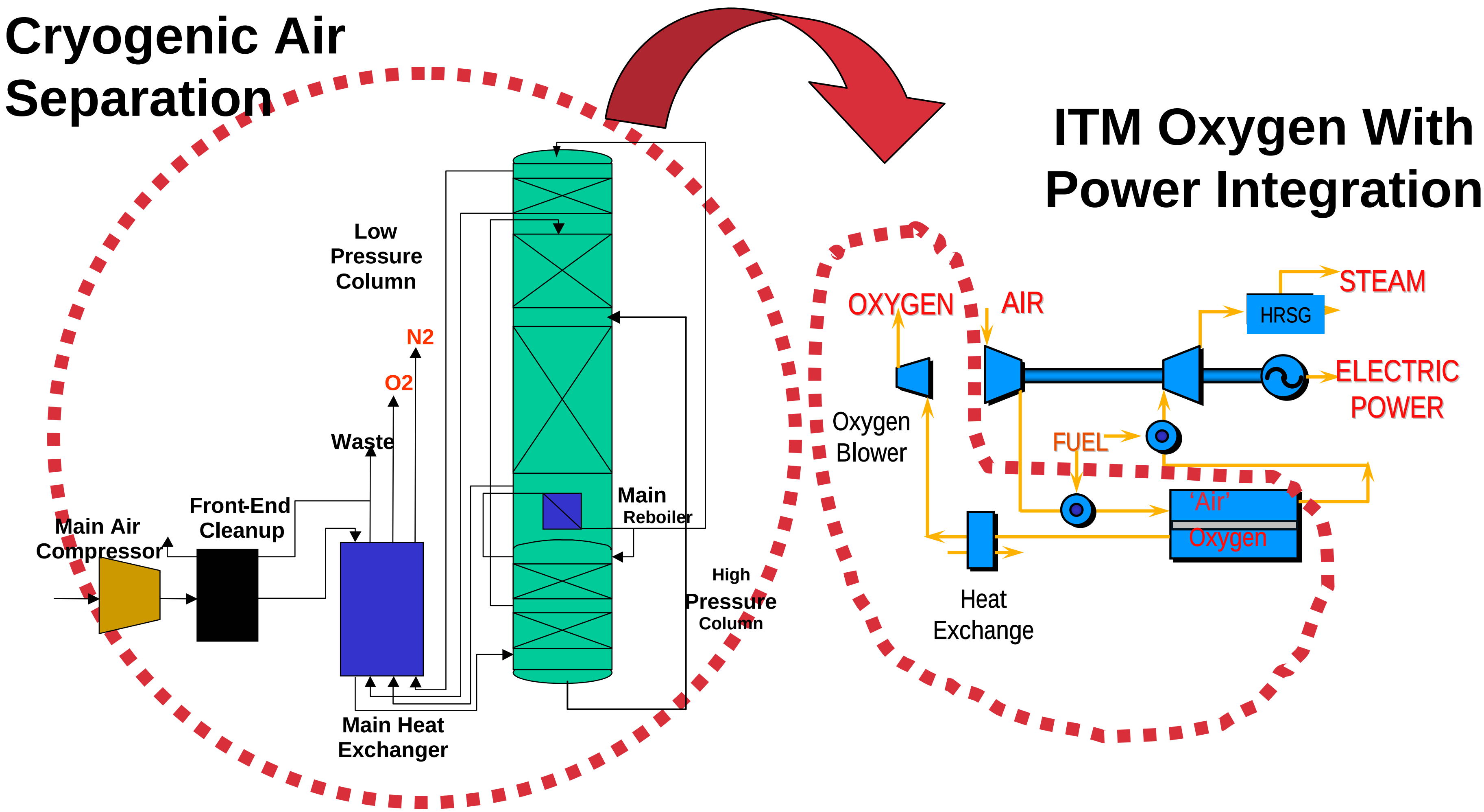
AIR PRODUCTS

ITM Oxygen integrates well with power generation cycles



ITM Oxygen separator integrated with a gas turbine-based power cycle

ITM Oxygen is Simpler and Requires Less Power



- ITM O2 Has Much Simpler Flow Sheet and >35% Less Capital
- ITM O2 Has 35-60% Less Compression Energy Associated with Oxygen Separation

AIR PRODUCTS

ITM Oxygen has Excellent Economic Performance in Many Applications

Application	Product: Oxygen (sTPD)	Product: Power (MW)	Savings (% of Cryo ASU): Capital for Oxygen	Savings (% of Cryo ASU): Power for Oxygen
IGCC	3200	458	35%	37%
Decarbonized Fuel†	2400	300	35%	36%
Enrichment*	1500	260	27%	69%
Oxyfuel†*	8030	500	48%	68%
GTL	12,500	n/a	20+%	n/a

†enables carbon capture

*uses existing gas turbine offerings

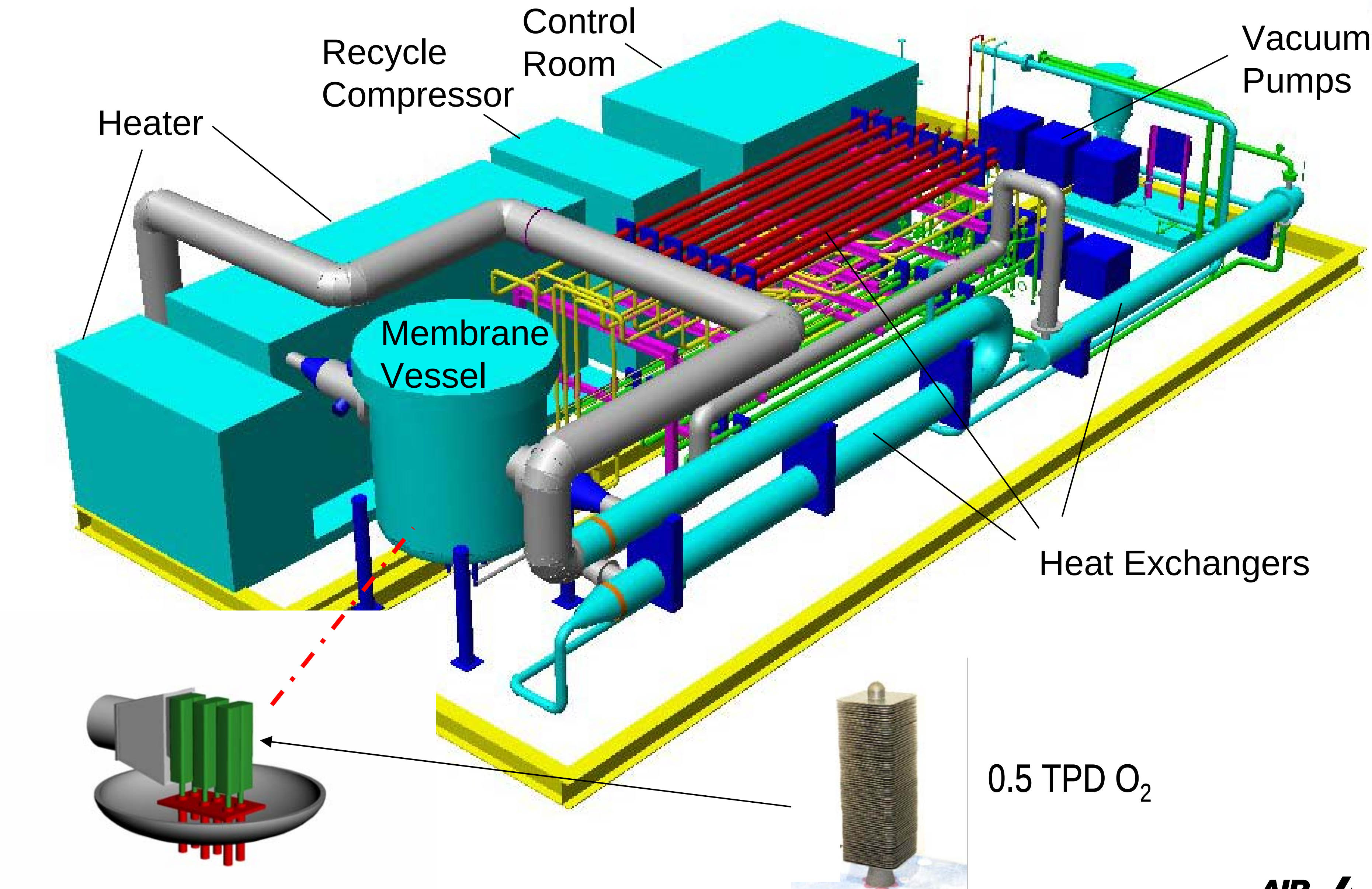
AIR PRODUCTS

ITM Oxygen Program

- **Goal: Reduce Cost of Oxygen by One-Third**
- **DOE/Air Products R&D started 1999 (11 year, $148 million)**
  - **Phase 1: Technical Feasibility (0.1 TPD O2)**
  - **Phase 2: Prototype (1-5 TPD O2)**
  - **Phase 3: Pre-commercial Development (25+ TPD)**
    - **Planning 150 TPD**
- **Development Team**

AIR PRODUCTS
U.S. DEPT. OF ENERGY
NovelEdge TECHNOLOGIES
GE Energy
CONCEPTS NREC
ceramatec
ELTRON RESEARCH
SIEMENS
PENNSTATE 1855
SOFCo EFS (McDermott)
University of Pennsylvania

5 TPD SEP Skid Design – Isometric

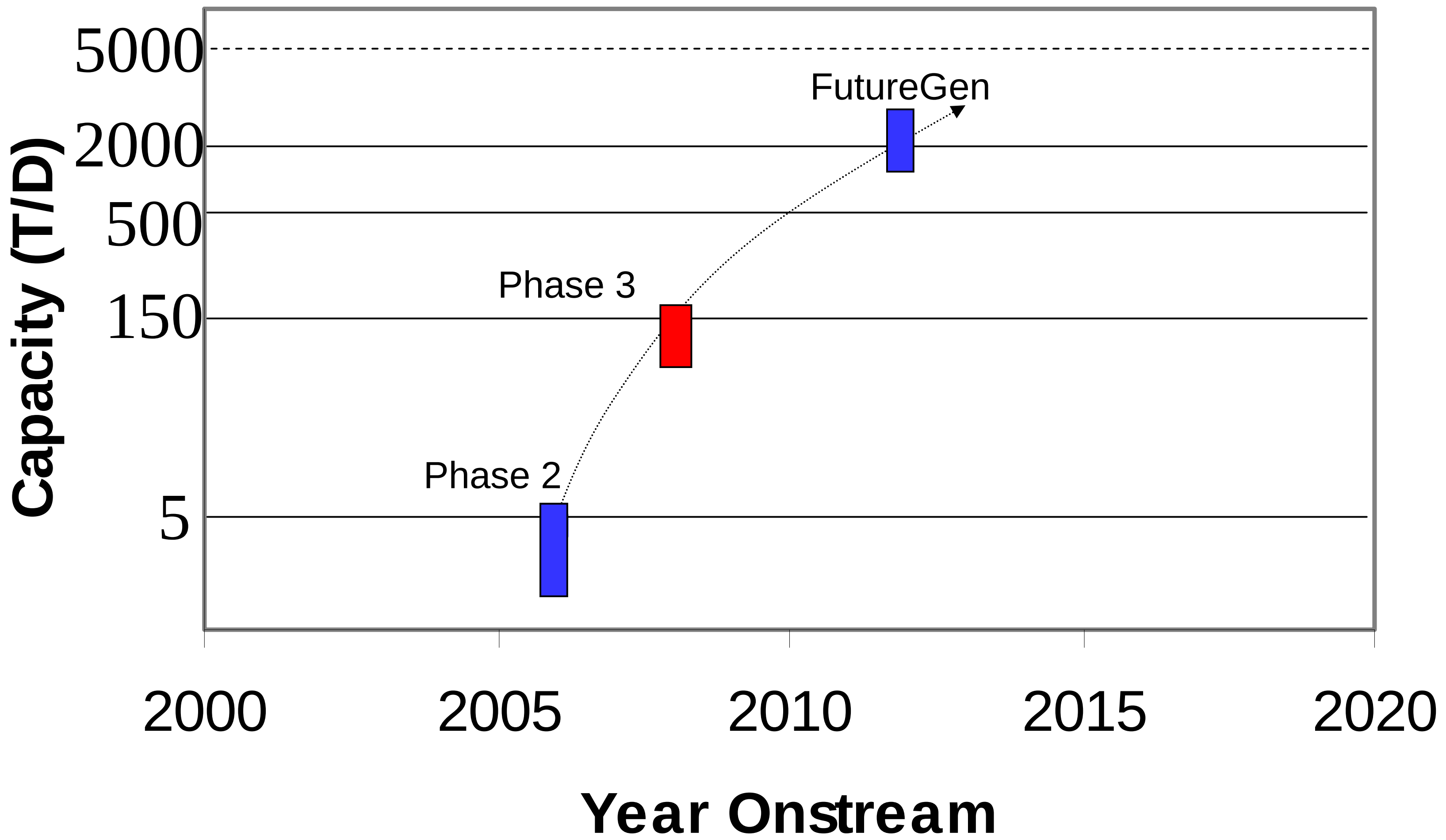


The SEP was started up in Oct. ’05, commissioned in April ‘06

Initial SEP work <u>highly successful</u>

- **Several trials with 0.5-TPD modules since May**
- **Demonstrated >99% oxygen purity from commercial-scale module and seal**
- **Oxygen flux consistently has met or exceeded expectations, and has been steady**
- **Currently running modules through start-up/shutdown cycles to test reliability**

Future Work: Phase 3 Development Plan meets DOE FutureGen Schedule and Market Timing



AIR PRODUCTS

Conclusions

- **Cryogenic air separation proven and available at scale**
- **Major Phase 2 ITM Oxygen development objectives have been met**
  - **Built and tested commercial-scale ITM Oxygen modules successfully**
- **Air Products and the U.S. DOE are planning an expanded Phase 3 to enable ITM Oxygen to produce large-tonnage quantities of oxygen in the FutureGen plant**

Acknowledgment: DOE/NETL

This paper was written with support of the U.S. Department of Energy under Contract No. DE-FC26-98FT40343. The Government reserves for itself and others acting on its behalf a royalty-free, nonexclusive, irrevocable, worldwide license for Governmental purposes to publish, distribute, translate, duplicate, exhibit and perform this copyrighted paper.

AIR PRODUCTS

Thank You…
tell me more

http://www.airproducts.com

ITM@airproducts.com
Phone: 610 481 4475
Fax: 610 706 7420

Development of Cost-effective Oxy-Combustion for Coal-fired Boilers

Hamid Farzan
The Babcock & Wilcox Company (B&W)

Sponsored By:
The Babcock & Wilcox Company
American Air Liquide (AAL)
U.S. DOE National Energy Technology Laboratory (NETL)

Presented to:
2nd IEAGHG Int'l Oxy-Combustion Workshop
Windsor, CT, USA
January 25-26, 2007

a McDermott company

The Babcock & Wilcox Company

*Generating Powerful Solutions*SM

B&W Oxy-combustion Experience

- **1979 Numerical Modeling per request of a major oil company**
- **2000 Member CANMET**

Recent Developments with Air Liquide Collaborations

- **2001-2002 - Oxy-combustion with IL#6 coal performed at 5 million Btu/hr SBS facility, sponsored by the State of Illinois**
  - Substituted secondary air with recycled flue gas & oxygen
  - Gained experience with oxygen/flue gas mixing and combustion
- **2003-2004 - Oxy-combustion with PRB, sponsored by DOE**
  - Demonstrated oxy-combustion at 5-million Btu/hr, achieved stable low-NO_x flame with acceptable heat transfer conditions
- **2005-2006 - Economic analysis**
  - Working with DOE, Parsons, Air Liquide
  - Oxy-combustion compared favorably to amine scrubber

B&W Current Oxy-Combustion R&D

New Oxy-Combustion ready Facilities

- **6 million Btu/hr – SBS- II**
- **100 million Btu/hr (30 MW_{th}) CEDF**

Currently Planning for:

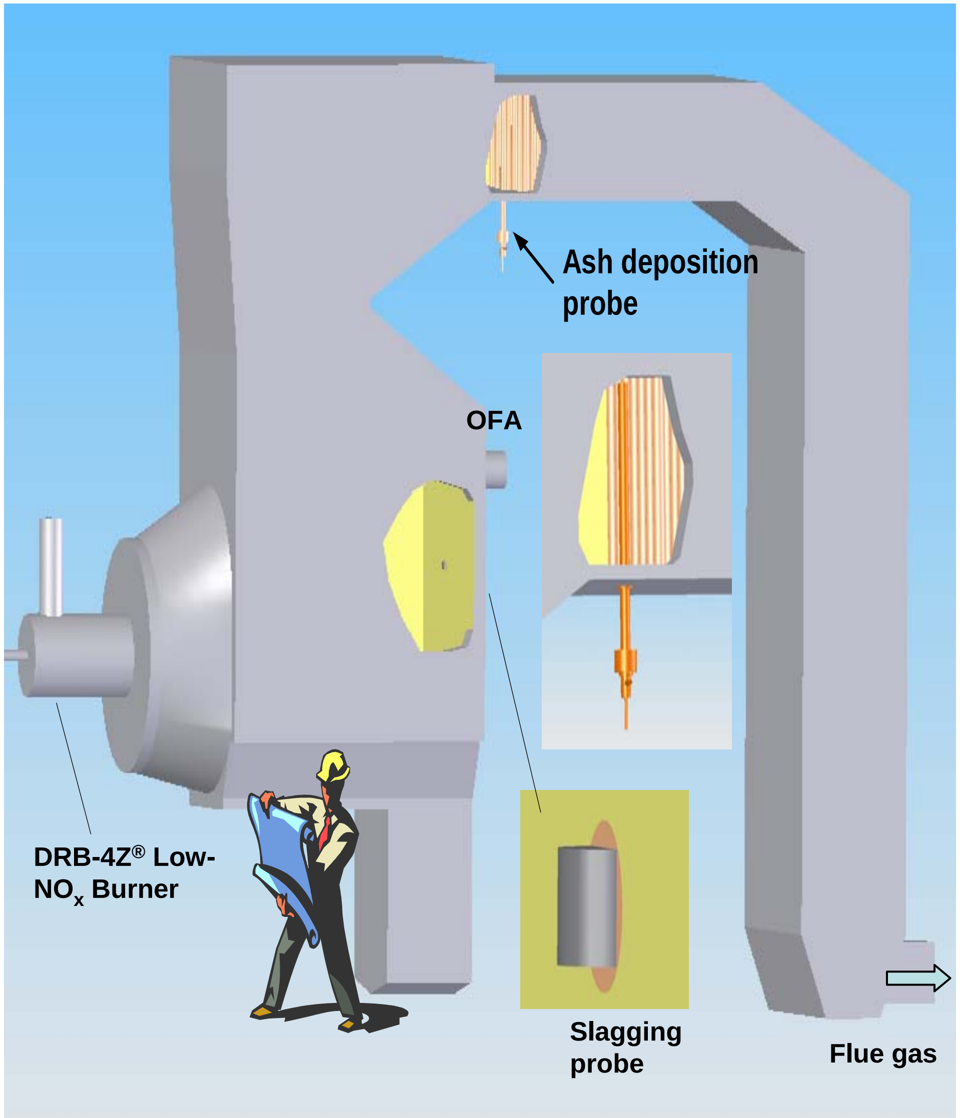
- DOE Oxy-cyclone

- USC Materials Oxy-combustion

- CEDF Oxy-Combustion Campaign

- Sask Power

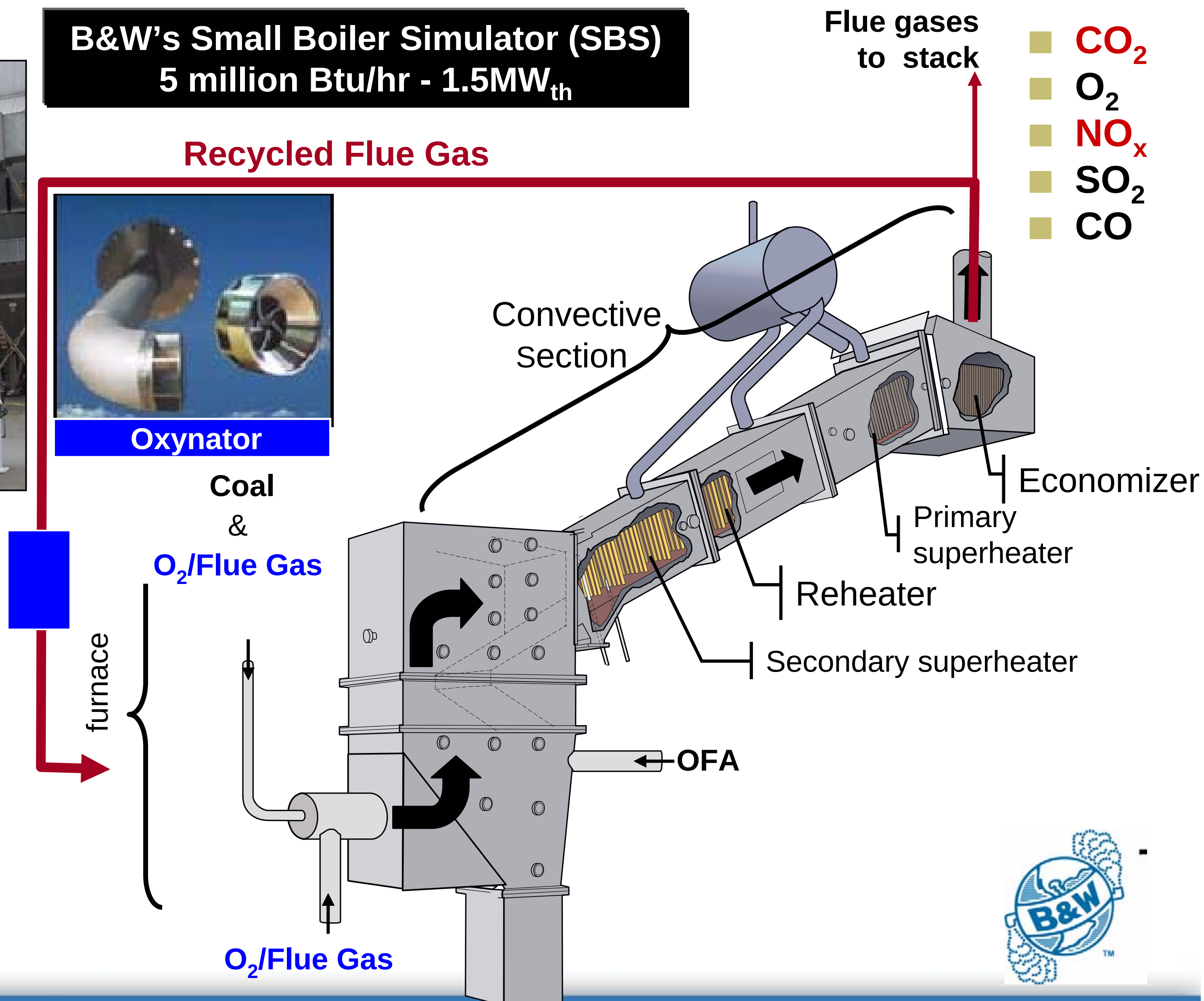
2nd to 4rd Quarter 2007 Testing



Pilot Modifications for Oxy-combustion

B&W's Small Boiler Simulator (SBS)
5 million Btu/hr - 1.5MW$_{th}$

Oxygen Supply System

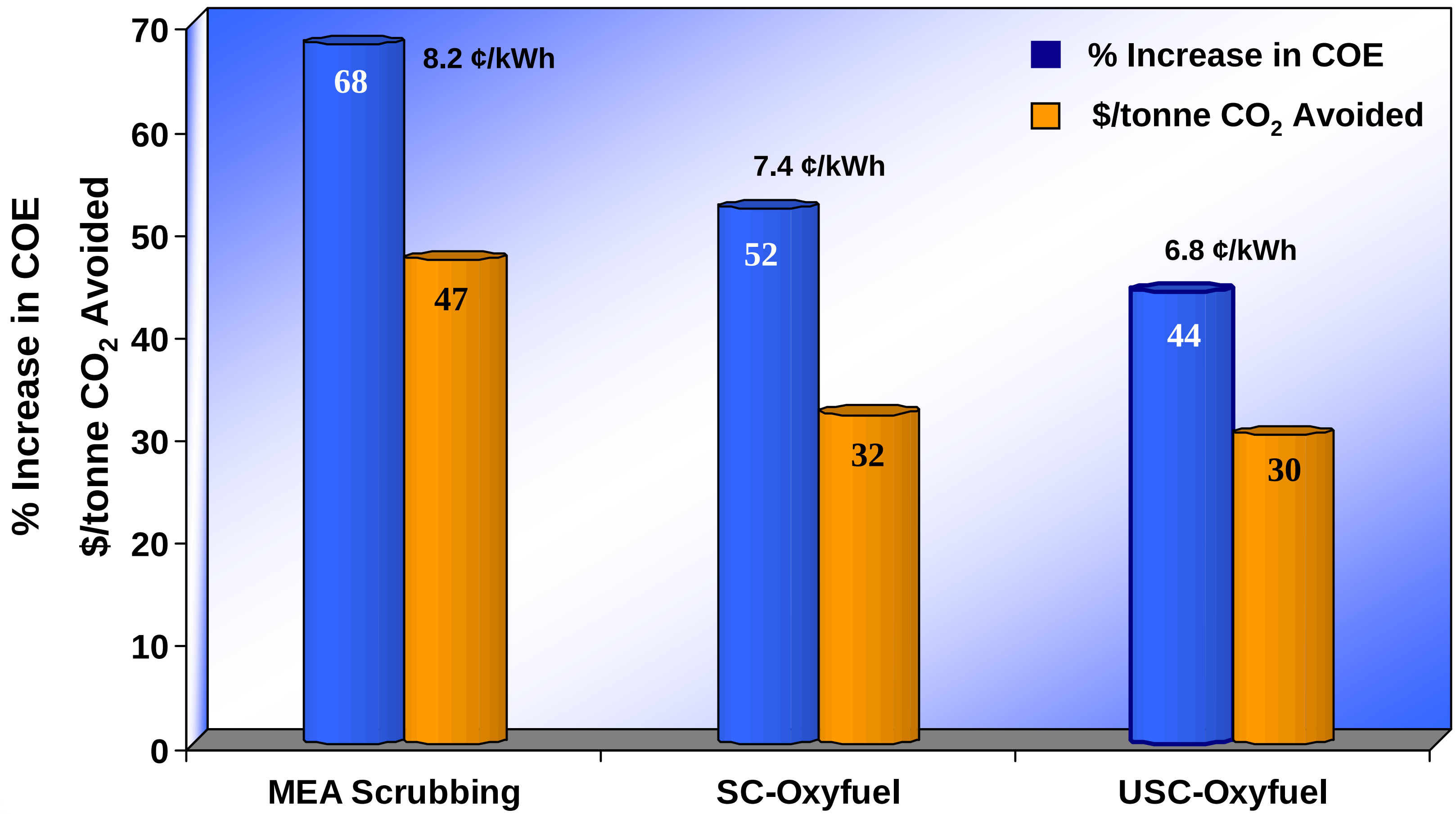


Heat Transfer Characteristics At 5 MBtu/hr Typical Test Results with PRB Coal

	Air Firing	Oxy-combustion
Boiler Mass Flow Rate, lb/hr	4,167	4,030
Burner Stoichiometry	0.86	1.05
FEGT, F	1797	1880
Convection Pass Temp., F	555	547
Convection Pass Heat absorption, % Heat Input	43.6	46.8

- ⇒ Similar mass flow rates in the boiler
- ⇒ Higher burner stoichiometry during oxy-combustion for flame stability
- ⇒ Similar convection pass heat absorption and exit temperature

CO_2 Capture Mitigation Costs



MEA Scrubbing: Air Fired SC Boiler, Econamine FG+ CO_2 Capture

Note: Economic study was performed by Parson, DOE.
Expected final report by Spring 2007

Current Major Oxy-combustion DOE Contract

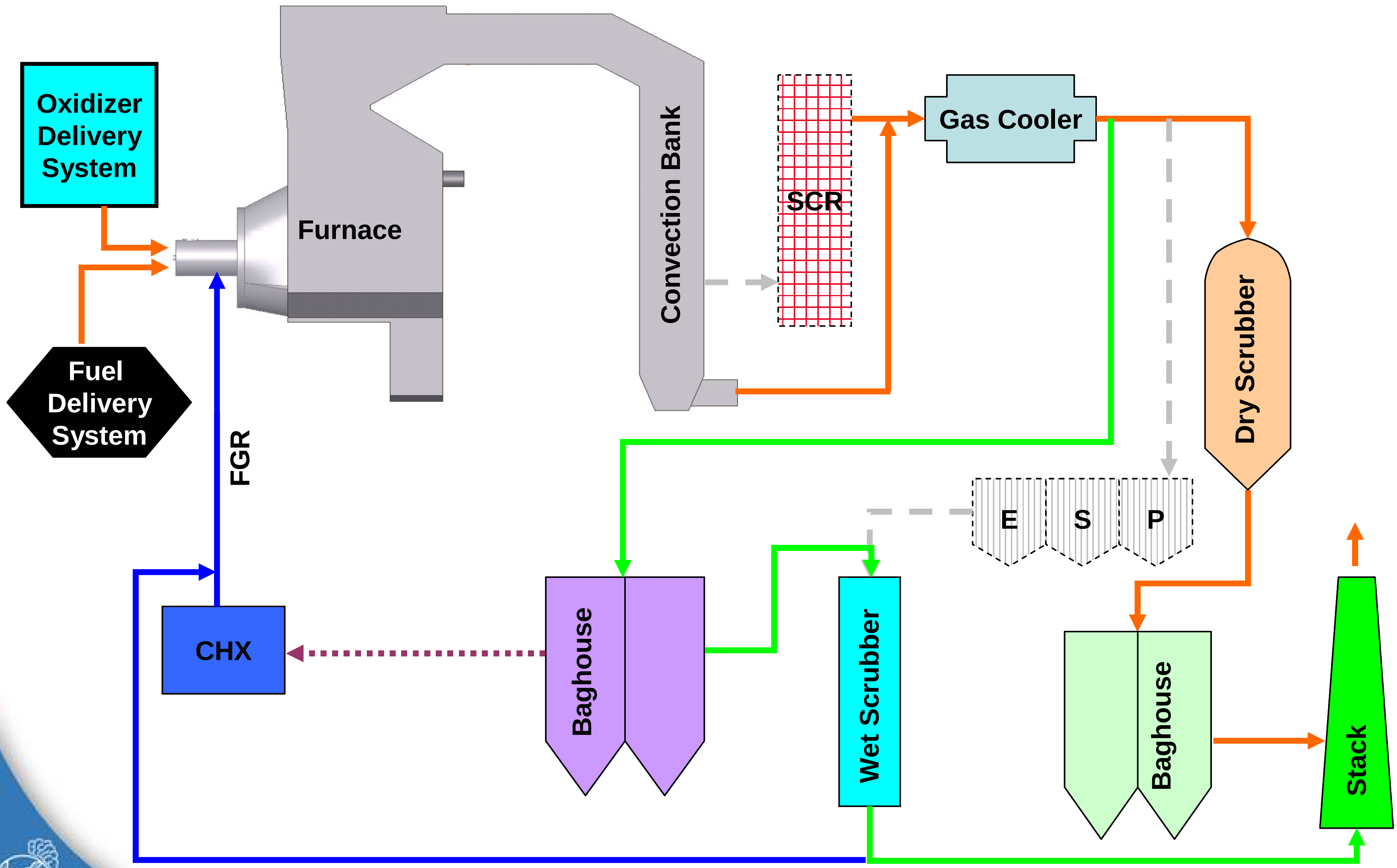
- **Oxy-Combustion for Retrofitting Existing Boilers – DOE**

Objective:

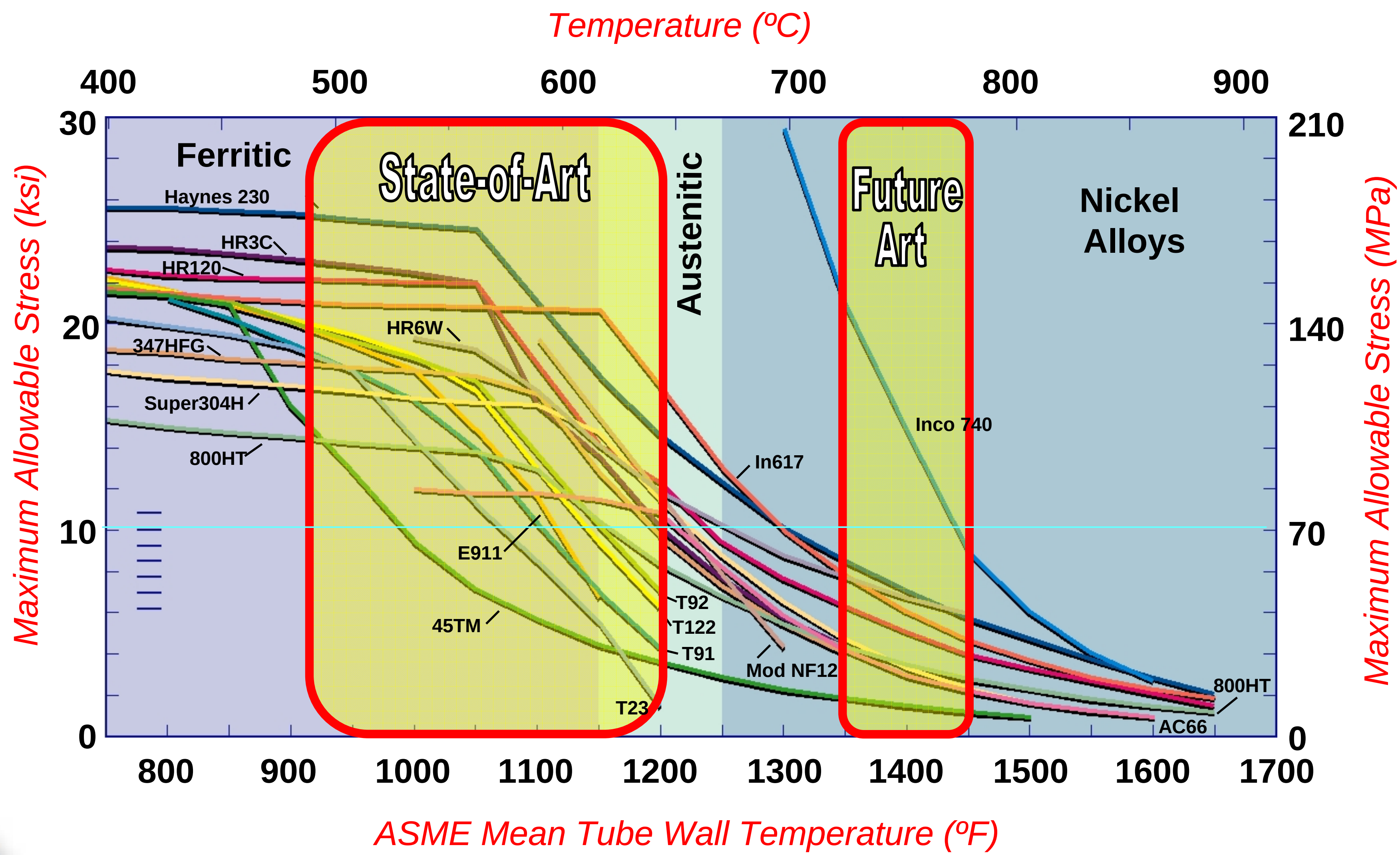
- **To expand applicability of oxy-combustion to different coal ranks and boiler types (e.g. cyclone firing)**
  - **Optimization of ASU, boiler, flue gas purification, transportation and sequestration components**
  - **Oxy-combustion with lignite, wall-firing (2nd & 3rd Quarter 2007)**
  - **Oxy-cyclone with bituminous, PRB, & lignite (4th Quarter 2007)**
  - **Engineering feasibility study – 2008**
    - **One wall-fired and one cyclone unit**

Team: B&W, Air Liquide, Battelle

6-Million Btu/hr SBS-II General Layout



Boiler Material Options for Ultra-Supercritical Plants



Proposed Oxy-combustion Fireside Corrosion Evaluation

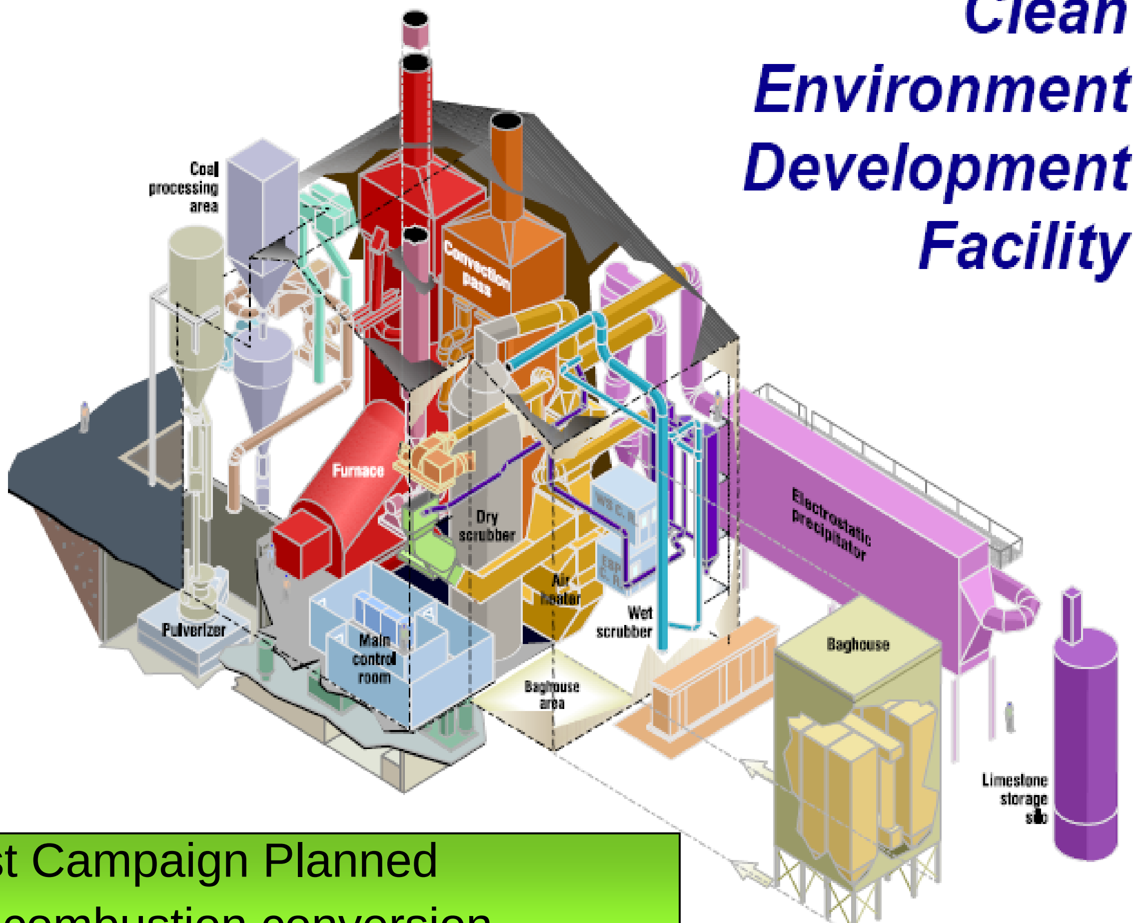
Objective: Materials Performance in Oxy-combustion Ultrasupercritical Boiler

Approach:

- **Use the SBS to simulate an oxy-combustion ultrasupercritical boiler and collect furnace gas and coal ash samples at locations representative of the upper and lower furnace**
- **Perform laboratory fire side corrosion tests which expose candidate boiler materials to the furnace gases and coal ash compositions determined in the SBS**
- **Compare these results with those determined for conventional ultrasupercritical exposures**
- **Use the results to guide material selection**

A proposal to DOE and OCDO under, "Boiler Materials for Ultra Supercritical Coal Power Plants"

30 MW_{th} Oxy-Combustion Test Campaign B&W Test Facility (CEDF)



Clean Environment Development Facility

2007 Test Campaign Planned

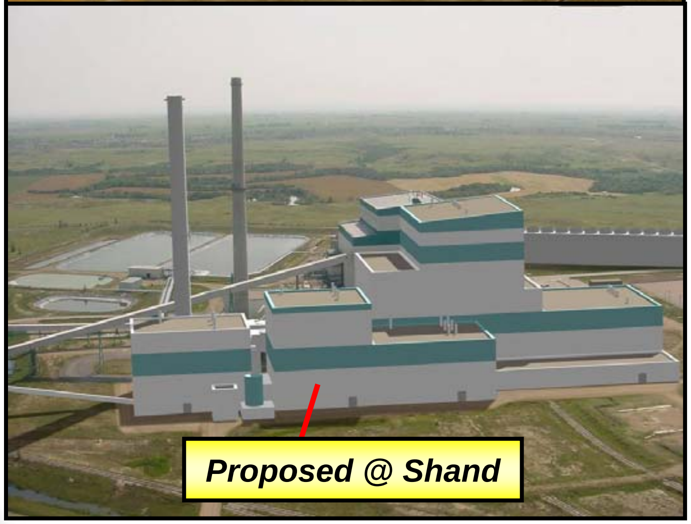
- Full oxy-combustion conversion
- Three coal types (ranks)
- Utility Advisory Group (to be formed)

Current Major Oxy-combustion Campaign

Objective: To Demonstrate at 30 MW_{th} Oxy-Combustion

- **Near-full-scale burner fed directly by an on-line pulverizer**
  - **Pulverizer performance is affected by flue gas composition**
  - **Pulverizer may require more recycle gas than air to maintain acceptable performance especially with low-rank coals**
  - **New burner design is necessary**
- **Three coals will be tested: lignite, PRB, and eastern bituminous**
- **Will demonstrate B&W's novel concept for controlling flue gas moisture content via a wet scrubber with integrated cooling**
- **Support Sask Power project development**

SaskPower Clean co_2al Project Summary



- **Many aging units in SaskPower system will be retired**
- **New capacity is needed**
  - **300 MW by 2012**
  - **600 MW by 2016**
- **SaskPower has selected the Babcock & Wilcox (B&W) and Air Liquide (AL) alliance to develop a Near Zero Emission Plant (NZEP)**
- **B&W and AL Oxy-Combustion process selected over IGCC and CO_2 Scrubbing**
- **Oxy-Combustion replaces air with pure oxygen (O_2) and recirculated gas (CO_2), and enables CO_2 capture and storage**

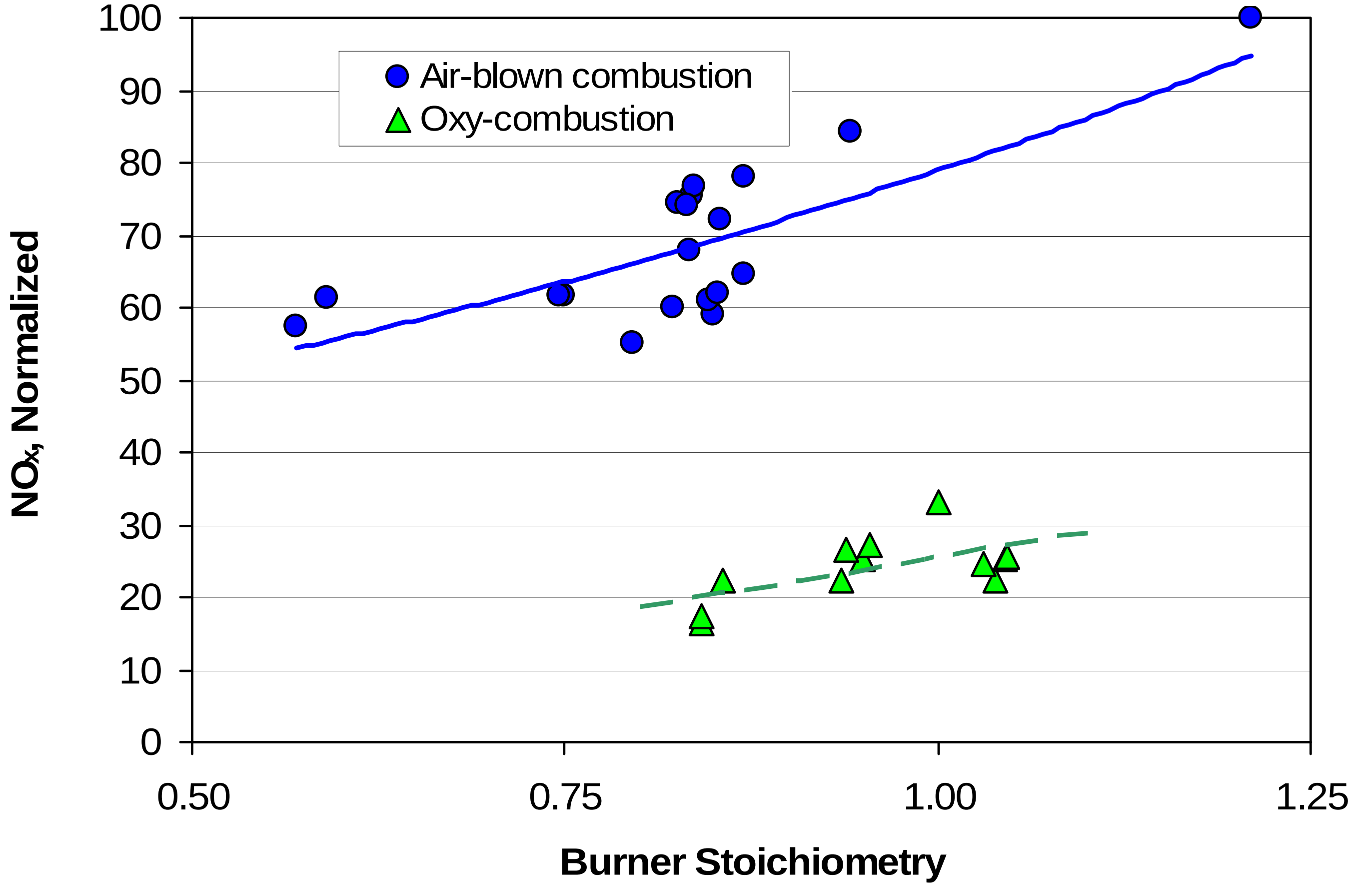
a McDermott company

The Babcock & Wilcox Company

Generating Powerful Solutions℠

1-800-BABCOCK
www.babcock.com

NO_x Emissions



- ***Substantially Lower NO_x Emissions :***
  - **Lower Nitrogen: Lower Thermal NO_x**
  - **Recycled Flue gas: NO_x is destroyed by reburning Mechanism**

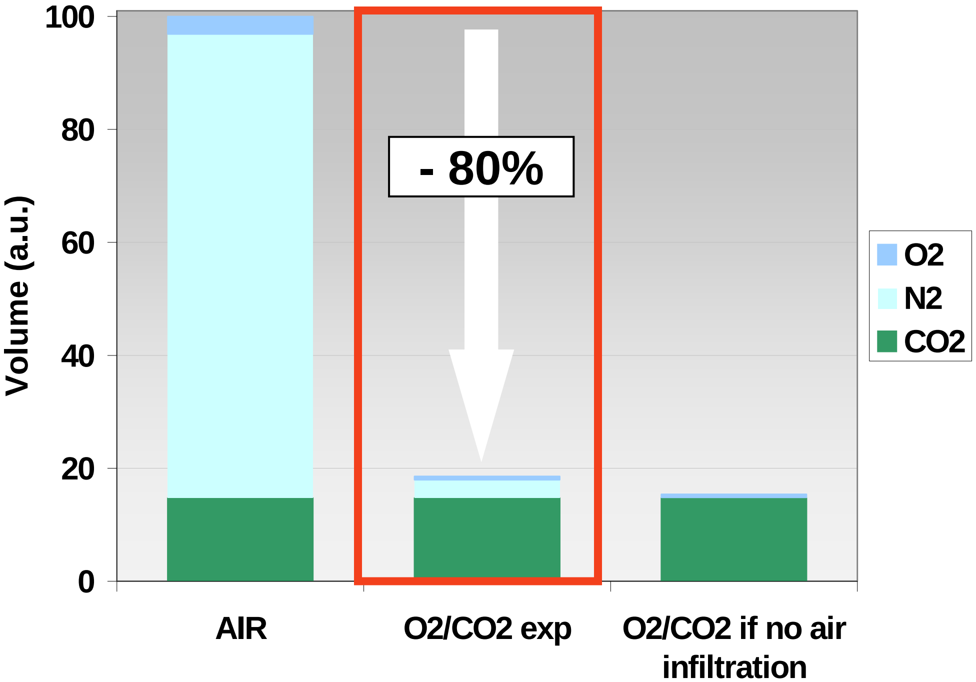
Flue Gas Volume and CO_2 Concentration

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

	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

Flue gas volume



a.u. = Arbitrary Units

Work Scope

Phase I - Pilot-Scale Evaluation of Oxy-Combustion

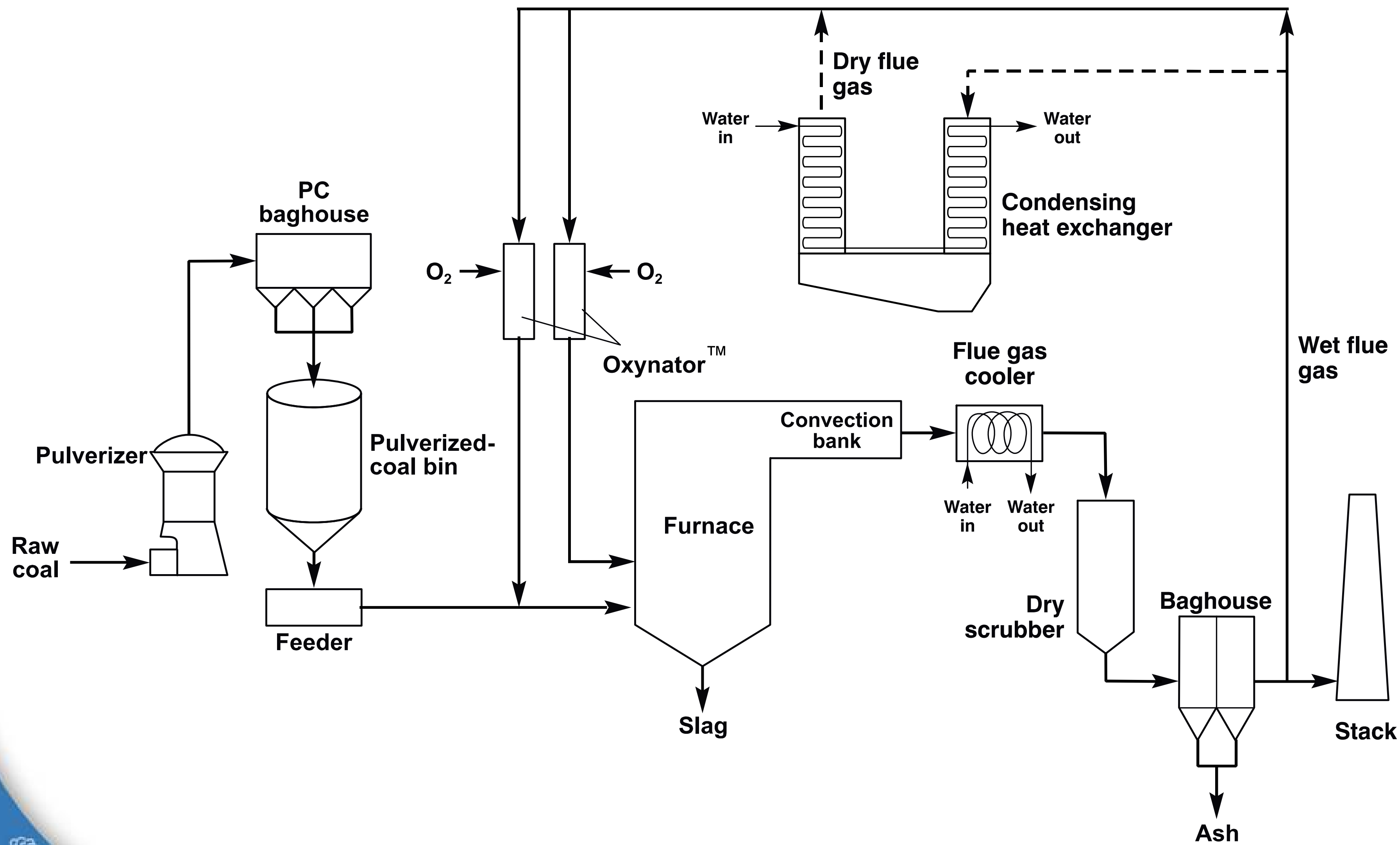
- **Task 1: Specification of Flue Gas Purification, Compression, Transportation, and Sequestration Requirements**
  - **Subtask 1.1: CO_2 Transportation & Sequestration**
  - **Subtask 1.2: Flue Gas Purification and Compression Train**
  - **Subtask 1.3: Environmental Equipment Requirements**
- **Task 2: Pilot-Scale Evaluation**
  1. **Cyclone - Bituminous, PRB, and lignite**
  2. **Wall-firing - Lignite**

Work Scope

Phase II - ENGINEERING & ECONOMICS EVALUATION OF FULL-SCALE BOILERS

- **Task 3: Boiler Selection and Data Gathering**
  - a representative reference cyclone and wall-fired Boilers
  - full-size (500-600 MWe)
- **Task 4: Preliminary System Design**
  - ASU Specifications and Oxygen Delivery System
  - Boiler Modifications
  - Flue gas Purification & Compression
  - CO2 Transportation and Sequestration
  - System Integration
- **Task 5: Economic Evaluation**
- **Task 6: Reporting**

Schematic of SBS in Oxy-Combustion Mode

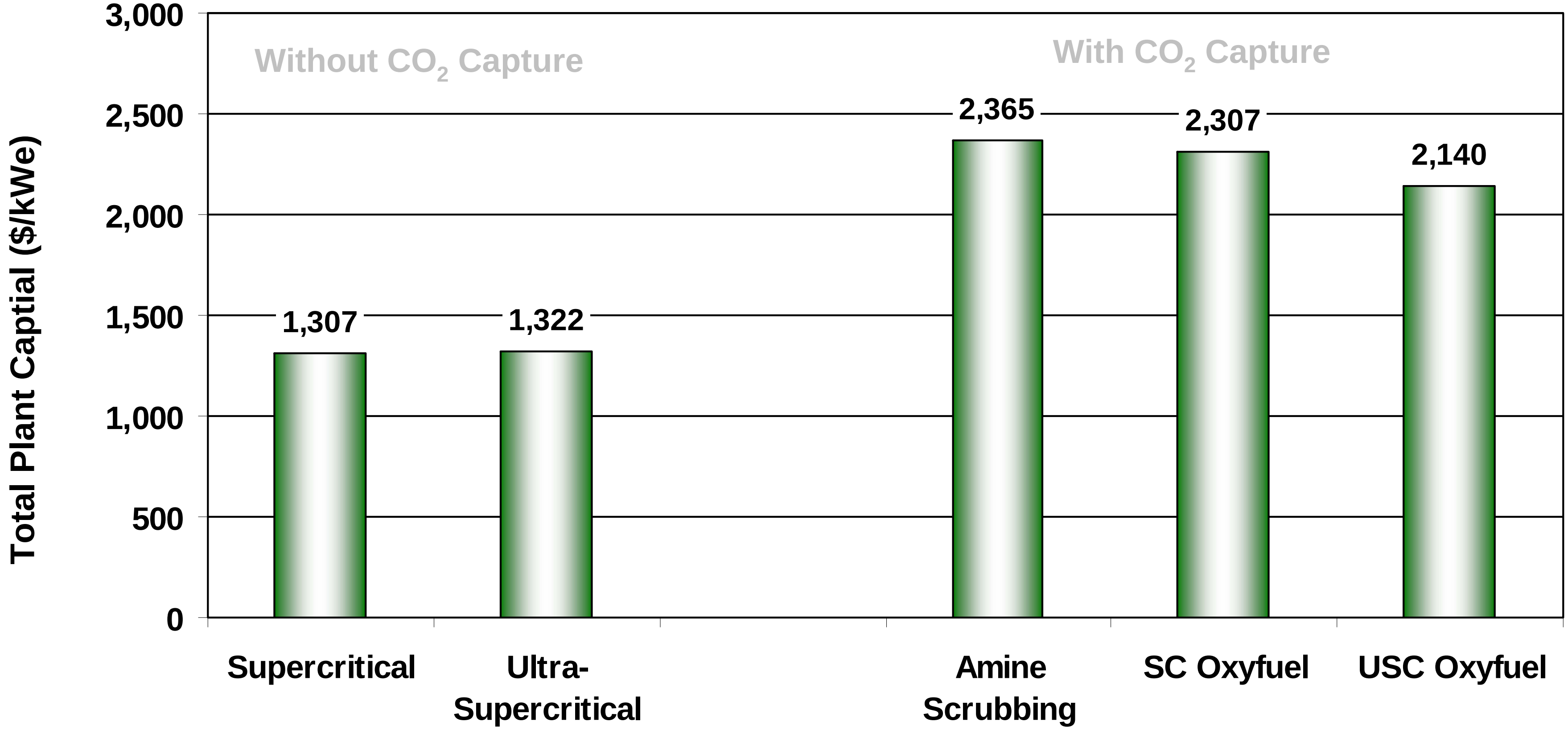


Oxy-combustion Economics

- **2005-2006 -** Working with DOE, Parsons, Air Liquide

- Performed study on:
  - Supercritical Boiler
    - » **1100X1100 F at 3500 PSi**
  - Ultra Supercritical Boiler
    - » **1300X1350 F at 4000 PSi**

Total Plant Capital Cost Summary



CO_2 Capture increases Total Plant Cost by 60-80%

Note: Economic results under review. Final results available summer 2006.

Doosan Babcock Energy

Doosan Babcock Oxyfuel Development Plans

IEAGHG International Oxy-Combustion Workshop
2nd Workshop, 25th – 26th January 2007, USA

Ragi S Panesar

Date: 25th January 2007
Department: Process Technology & Development

Doosan Heavy Industries acquires Mitsui Babcock

Parent Company Update

- On 6 November 2006 our Parent company, Mitsui Engineering & Shipbuilding, signed an agreement to sell 100% of the Mitsui Babcock business to Doosan Heavy Industries (UK) Limited, for JPY 20 billion (approx £100m). Completion of the deal is expected by January 2007.
- Doosan Heavy Industries (UK) Limited is a subsidiary of Doosan Heavy Industries & Construction, the South Korea-based engineering and construction company. Upon completion of the deal Mitsui Babcock will be known as Doosan Babcock.

Presentation

- Doosan Babcock – Carbon Capture Projects
- Doosan Babcock Oxyfuel Boilers – the way forward
- Concluding Remarks

Presentation

- Doosan Babcock – Carbon Capture Projects
- Doosan Babcock Oxyfuel Boilers – the way forward
- Concluding Remarks

Carbon Capture Projects

Current Projects include :

- UK DTI : OXYCOAL-UK : Phase 1
- EU FP6 : ENCAP (Oxyfuel)
- EU FP6 : CASTOR (Post Combustion)
- DTI Project 407 : ASC BT Retrofit with CO_2 Capture
- DTI Project 366 : New-Build CO_2 Capture Options for the Canadian Market
- EU RFCS : OxyMod : Oxyfuel Combustion Modelling
- IEA GHG : CO_2 Capture Ready Project

- GHGT8
- GHGT8
- GHGT8

Recent / Completed Projects include :

- IEA GHG Studies - new build ASC PF Plant
- Oxyfuel Design / Feasibility Studies (BP, Air Products)
- EU funded trials of OXYFUEL Firing

- GHGT7
- GHGT5

Presentation

- Doosan Babcock – Carbon Capture Projects
- Doosan Babcock Oxyfuel Boilers – the way forward
- Concluding Remarks

Doosan Babcock Oxyfuel Boilers – the way forward
Three Stage Development Programme

- To develop a competitive Oxyfuel firing technology suitable for full scale plant application post-2010.

- A staged approach to the development and demonstration of Oxyfuel technology:-

  Stage 1 : Fundamentals and System Design

  Stage 2 : Modified Design Tools and Component Testing

  Stage 3 : Reference Designs

OXYCOAL- UK collaboration

Project 407 ASC Retrofits with CO_2 Capture

GHGT8

Project Team

Doosan Babcock, ALSTOM, Air Products, E.ON UK, Imperial

Sponsors

E.ON UK, Drax, EDF, SSE, RWE, SP

Technical Steering Committee: Doosan Babcock, ALSTOM, E.ON UK, Air Products, Drax, EDF, SSE, RWE, SP, Imperial

Phase 1 Project

Underpinning Technologies

Project Team

Doosan Babcock
Imperial, Nottingham,
Air Products, E.ON UK, RWE, BP

Sponsors

Doosan Babcock
UK Utilities

Technical Steering Committee: Doosan Babcock, Imperial, Nottingham, Air Products, E.ON UK, UK Utilities

Phase 2 Proposal

Development and Demonstration of Oxycoal Combustion System

Project Team

Doosan Babcock,
Imperial,
Nottingham

Sponsors

Doosan Babcock
European Utilities

Technical Steering Committee: Doosan Babcock
Imperial, Nottingham, European Utilities

Doosan Babcock Oxyfuel Boilers – the way forward
Three Stage Development Programme : Stage 1

- **Stage 1 (06-08) Fundamentals and System Design**
  - Oxyfuel safety issues and design guidelines
  - Oxyfuel combustion fundamentals (lab & CFD studies)
  - Oxyfuel NOx formation (lab & CFD studies)
  - Oxyfuel corrosion studies
  - Oxyfuel heat transfer characteristics
  - Basic design and flowsheets
  - Basic efficiency calculations
  - Basic costing information

160kWt Facility

- **OXYCOAL-UK : Phase 1 : Contributes to above and comprises of:-**

1. **Combustion Fundamentals**
   Drop tube furnace testing for devolatilisation, char combustion and fuel-N partitioning; CFD analysis of data; application to plant via CFD : six UK / world traded coals.

2. **Furnace Design & Operation**
   Pilot scale testing (1MWt) to investigate slagging, fouling, and corrosion; laboratory scale testing on corrosion; investigation of ash.

3. **Flue Gas Clean-up / Purification**
   Pilot scale testing (160kWt) of post-combustion clean-up technology, including interaction with SCR and sorbent injection technologies.

4. **Generic Process Issues**
   Including reliability, availability, maintainability, operability, transient operation, safety/layout, transport and storage.

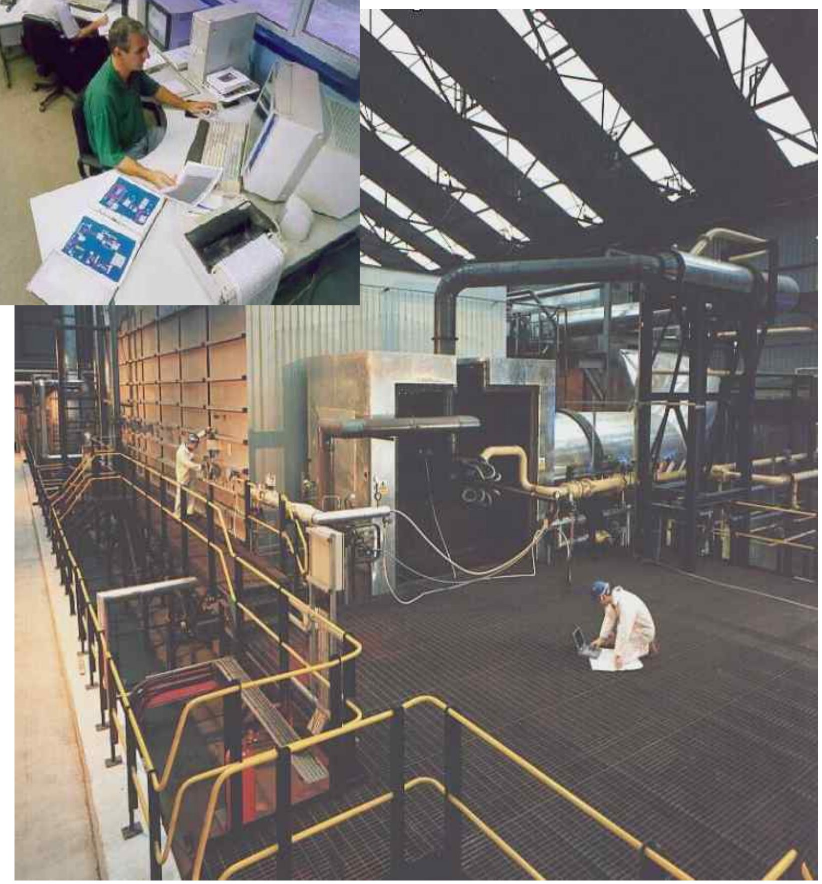
Three Stage Development Programme : Stage 2

Proposal

MBTF to be converted to Oxyfuel

The Multi Fuel Burner Test Facility was commissioned in Renfrew in 1999 and subject to UK DTI support will be converted to Oxyfuel PF firing.

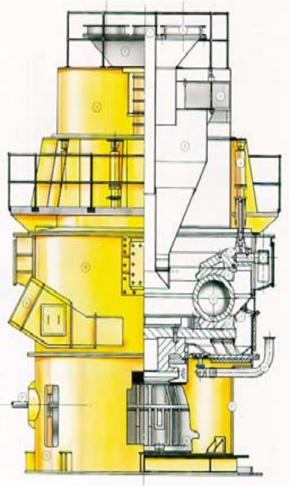
It is proposed to demonstrate full-size utility oxy-coal combustion in a collaborative project.



Doosan Babcock Oxyfuel Boilers – the way forward
Three Stage Development Programme : Stage 2

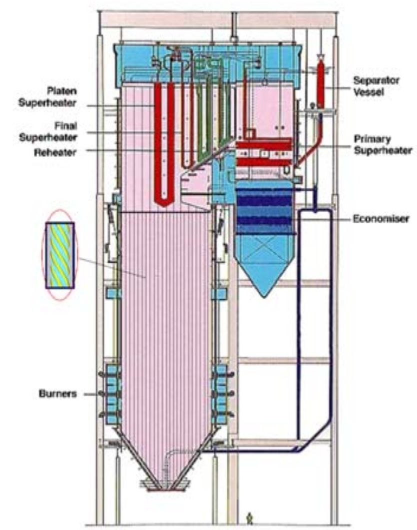
- **Stage 2 (07-09) Modified Design Tools and Component Testing**
  - Design rules for combustion efficiency prediction in oxyfuel flue gas
  - Design rules for NOx prediction in oxyfuel PF flue gas
  - Design rules for furnace and boiler performance in oxyfuel PF flue gas
  - Design rules for oxyfuel PF burners
  - Continuation of oxyfuel corrosion studies
  - Full scale rig test of oxyfuel burner : OXYCOAL-UK : Phase 2
  - Other component testing via participation in the Vattenfall 30MWth test

- **OXYCOAL-UK Phase 2 : Three main tasks**:
  - Convert Doosan Babcock's full-scale burner test facility to oxyfuel
    - Oxygen supply
    - Flue gas recycle system (fans, ducts, cooler, heater, etc.)
  - Design and build full-scale utility oxycoal PF burner
    - Derived from air-firing experience
  - Demonstrate a full-scale utility oxycoal PF burner
    - Start-up, transition from air to oxyfuel, load change
    - Emissions (NOx, SO_2, CO, etc.)
    - Heat transfer



Oxyfuel Boilers – the way forward
Three Stage Development Programme : Stage 3

- **Stage 3 (09-10) Reference Designs**
  - Develop full reference design as basis of commercial offering
  - Cost out reference design
  - Analyse and predict availability and reliability of commercial offering
  - Analyse and predict system efficiency and finalise integration with other plant



2005 2006 2007 200 8 2009 2010

Stage 1

Stage 2

Stage 3

Doosan Babcock Energy

Presentation

- Doosan Babcock – Carbon Capture Projects
- Doosan Babcock Oxyfuel Boilers – the way forward
- Concluding Remarks

Concluding Remarks

- Work to date has demonstrated Oxyfuel technology as a technically viable solution for CO_2 Capture that combines well proven, commercially available components with minimal risk.

- Doosan Babcock conceptual design for first generation Oxyfuel CO_2 Capture PF Power Plant :-

  Wide experience base of air-fired PF power generation technology and an evolutionary approach to Oxyfuel CO_2 capture provides a foundation and confidence that this technology will be successfully commercialised by 2010.

“We remain committed to development and global implementation of carbon-abated Clean Coal Technologies as rapidly as the market allows”

Thank you for your attention

rpanesar@doosanbabcock.com

FUNDACIÓN "CIUDAD DE LA ENERGÍA"

Test Facility for Advanced Technologies for CO_2 Abatement and Capture in Coal Power Generation El Bierzo

STATE OF DEVELOPMENT

Prof. Dr. Vicente J. Cortés Galeano, Program Manager
Prof. Dr. Benito Navarrete Rubia
School of Engineering
University of Seville. Spain

IEAGHG International Oxy-Combustion Network
2nd Workshop
25th and 26th January 2007
Windsor, CT, USA

SCOPE OF THE PRESENTATION

- LA FUNDACIÓN
- ACTIVITIES AND OBJECTIVES. THE SITE
- RELEVANT ISSUES AND GENERAL DESIGN CRITERIA
- PLANT CONFIGURATION
- PROCESS DIAGRAMS
- TIME SCHEDULE. THE WAY FORWARD

FUNDACIÓN CIUDAD DE LA ENERGÍA

AN INITIATIVE OF THE SPANISH ADMINISTRATION

MINISTERIO DE EDUCACIÓN Y CIENCIA

→ FUNDACIÓN CIUDAD DE LA ENERGÍA ←

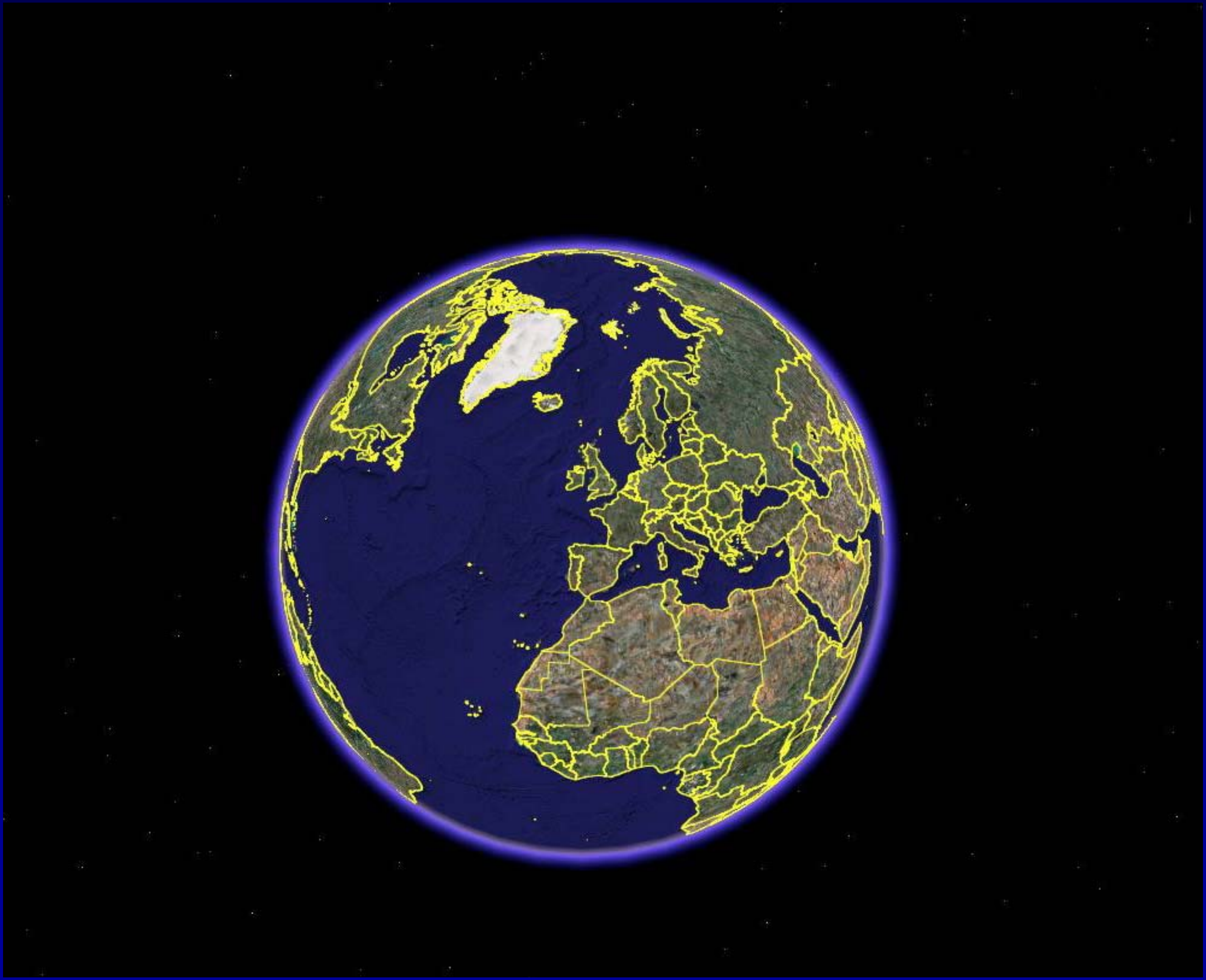
MINISTERIO DE INDUSTRIA Y ENERGÍA

CIEMAT ↑

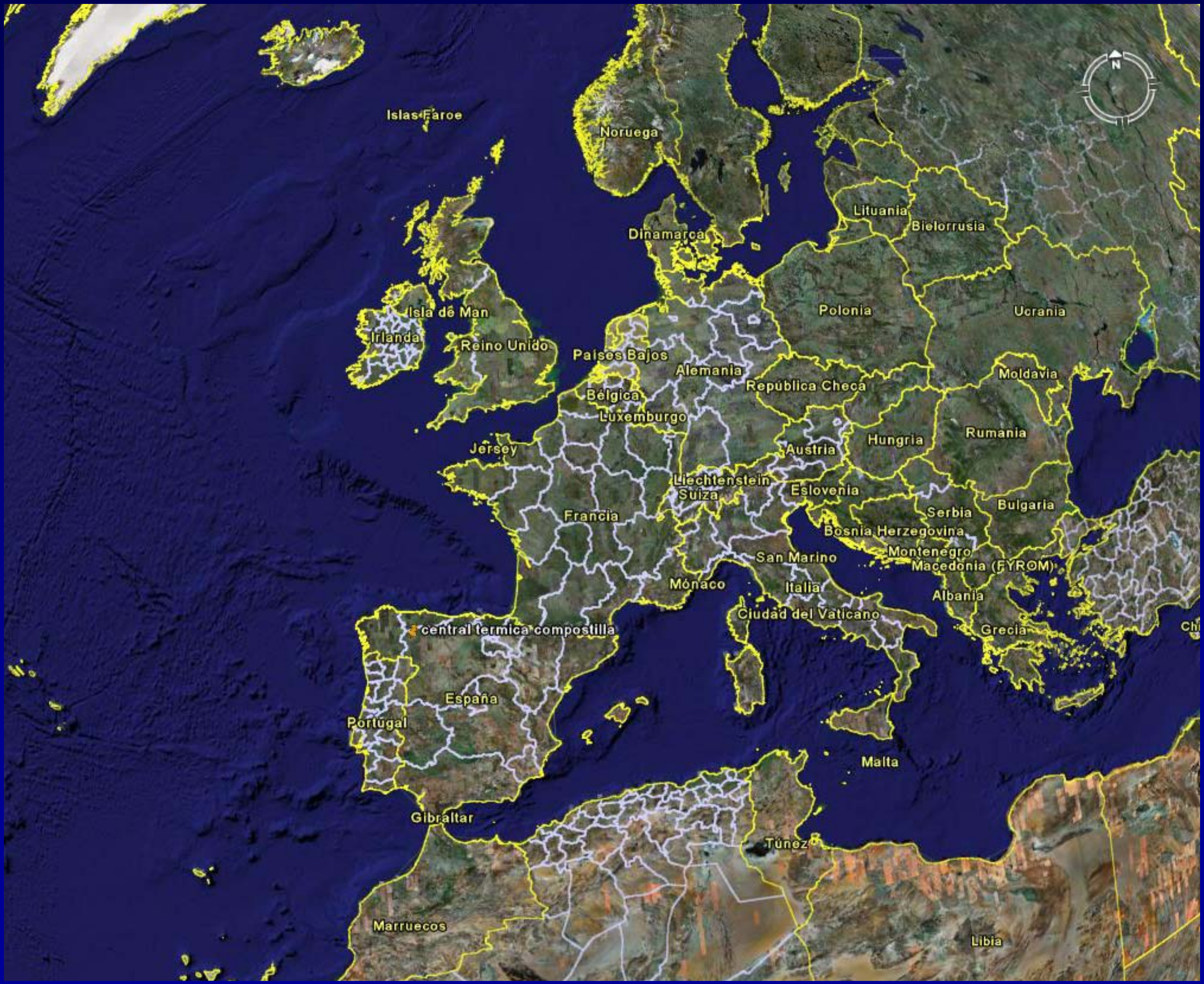
FUNDACIÓN CIUDAD DE LA ENERGÍA

THE SITE

EL BIERZO FACILITY FOR CO_2 ABATEMENT AND CAPTURE



THE SITE



Islas Faroe
Noruega
Dinamarca
Lituania
Bielorrusia
Isla de Man
Irlanda
Reino Unido
Polonia
Ucrania
Países Bajos
Alemania
República Checa
Moldavia
Bélgica
Luxemburgo
Rumania
Jersey
Austria
Hungría
Liechtenstein
Suiza
Eslovenia
Francia
Serbia
Bulgaria
Bosnia Herzegovina
Montenegro
San Marino
Macedonia (FYROM)
Mónaco
Italia
Albania
Ciudad del Vaticano
central termica compostilla
Grecia
España
Portugal
Malta
Gibraltar
Túnez
Marruecos
Libia

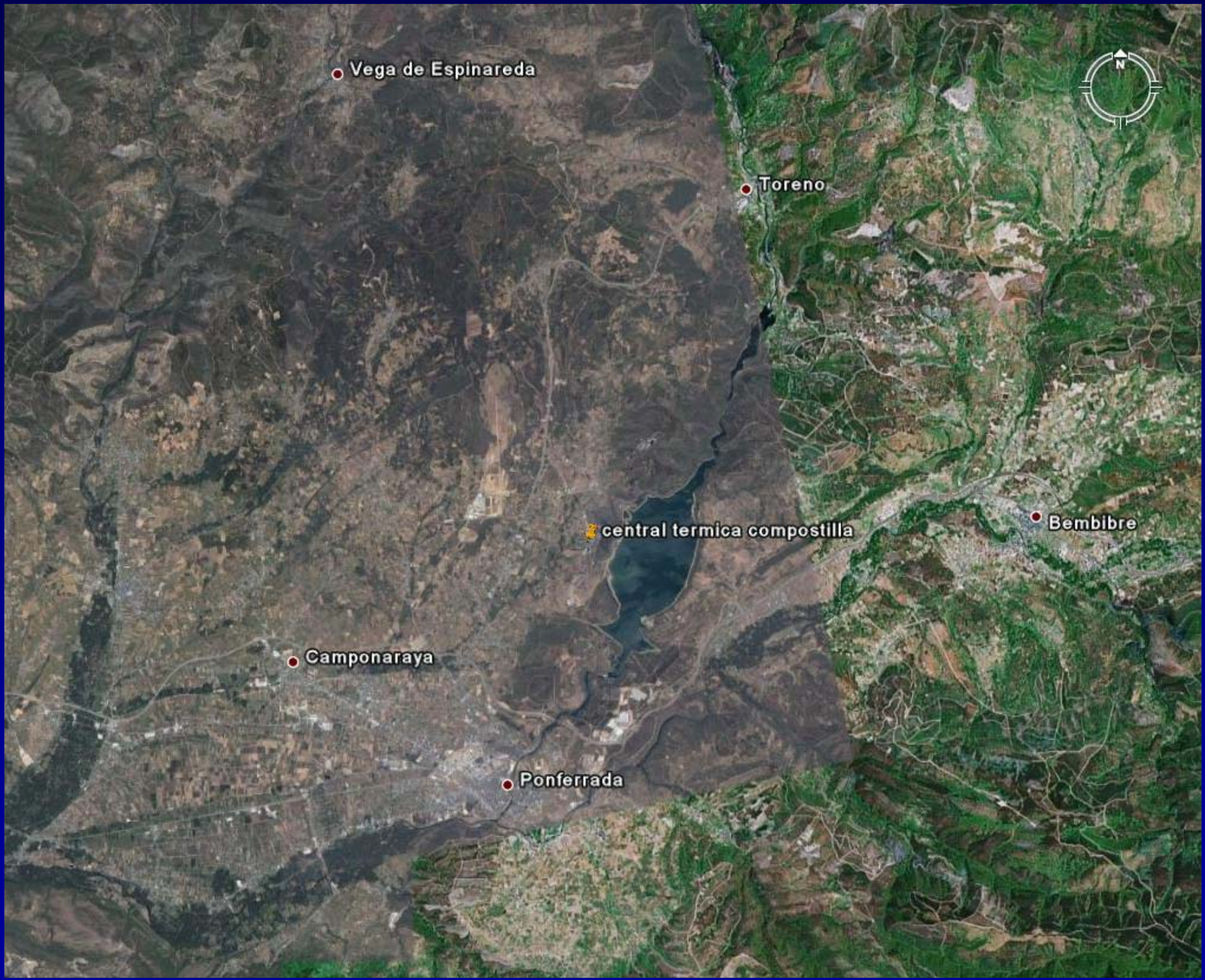
THE SITE


Île d' Oléron
central termica compostilla
Andorra la Vella
Barcelona
Madrid
Minorca
Mallorca
Portugal
Eivissa (Ibiza)
Formentera
Lisboa
El-Jazair
Gibraltar
Gibraltar
Tanger

FUNDACIÓN CIUDAD DE LA ENERGÍA

THE SITE

EL BIERZO FACILITY FOR CO_2 ABATEMENT AND CAPTURE



FUNDACIÓN CIUDAD DE LA ENERGÍA

THE SITE

EL BIERZO FACILITY FOR CO_2 ABATEMENT AND CAPTURE

THE SITE

OBJECTIVES AND ACTIVITIES

PROMOTE AND FINANCIALLY SUPPORT R&D+D INTO CO_2 CAPTURE AND STORAGE TECHNOLOGIES AND ABANDONED MINES RESTORATION

PROGRAM A

TEST FACILITY FOR CO_2 ABATEMENT AND CAPTURE

ADDRESSING

POST-COMBUSTION AND OXYFUEL TECHNOLOGIES AT EL BIERZO

PROGRAM B

CO_2 GEOLOGICAL STORAGE

ADDRESSING

TECHNOLOGICAL UNCERTAINTIES, PUBLIC ACCEPTANCE AND ASSESSMENT OF POTENTIAL FOR STORAGE IN SPAIN

PROGRAM C

ABANDONED LAND ACTION PLAN

ADDRESSING

RESTORATION OF LAND RESOURCES THROUGH REVEGETATION FOR LANDSCAPE RECOVERY

FUNDACIÓN CIUDAD DE LA ENERGÍA

RELEVANT ISSUES OF THE INITIATIVE (I)

EL BIERZO FACILITY FOR CO_2 ABATEMENT AND CAPTURE

EL BIERZO TEST FACILITY

- ✓ APPROACH CONSISTENT WITH INITIATIVES BEING DEVELOPED GLOBALLY
- ✓ PROVIDES SUPPORT FOR SPANISH CONTRIBUTION TO THE R&D EFFORT IN CCS IN EUROPE AND BEYOND
- ✓ IT IS CONCEIVED FOR OPERATION IN AN INTERNATIONAL CONTEXT, THROUGH COORDINATION WITH SIMILAR ACTIONS OUTSIDE SPAIN
- ✓ IT IS TO BE A FOCAL POINT FOR ACTIVITIES IN SPAIN IN CCS BRINGING TOGETHER REPRESENTATIVES OF THE FULL INDUSTRIAL CHAIN TOGETHER WITH RESEARCH/ACADEMIC INSTITUTIONS AND GOVERNMENT AGENCIES

RELEVANT ISSUES OF THE INITIATIVE (II)

EL BIERZO TEST FACILITY

- ✓ IT IS FULLY IN LINE WITH RECOMMENDATIONS OF ZEP SRA AS CO_2 CAPTURE USING OXIFUELLING IS RECOGNISED ONE OF KEY AREAS TO BE ADDRESSED
- ✓ THE MAIN OXYFUEL TRAIN OF THE FACILITY IS COMPLEMENTED WITH SEVERAL CO_2 SEPARATION ALTERNATIVES
- ✓ THE INITIAL FOCUS ON LOW VOLATILE FUELS (ANTHRACITE AND PETCOKE) PROVIDES AN ADDITIONAL DIFFERENTIATING FACTOR OVER OTHER TEST FACILITIES ELSEWHERE IN EUROPE

GENERAL DESIGN CRITERIA (I)

EL BIERZO TEST FACILITY

MODULARITY	LAY-OUT AS INDEPENDENT BUT INTERCONNECTED MODULES (COMBUSTION, OXYCOMBUSTION, FLUE GAS TREATMENT...) ALLOWING SIMULTANEOUS OR SEPARATE OPERATION FOR INDEPENDENT STUDY OF PROCESSES
FLEXIBILITY	OPERATION UNDER A WIDE RANGE OF OPERATING CONDITIONS, PARTICULARLY DIFFERENT DEGREES OF OXYCOMBUSTION
EXTENSION	LAY-OUT ALLOWING FOR EXTENSIONS AT A LATER STAGE IN LINE WITH ANY TECHNOLOGICAL PROGRESS AND / OR STRATEGIC DEVELOPMENT
EFFICIENCY	CONCEIVED GIVING GREAT IMPORTANCE TO HEAT INTEGRATION AND PERFORMANCE OPTIMISATION WITHOUT PUTTING INTO COMPROMISE REQUIREMENTS FOR FLEXIBLE TESTING

GENERAL DESIGN CRITERIA (II)

EL BIERZO TEST FACILITY

INTEGRATION

DESIGNED TO STUDY FULL PROCESS INTEGRATION OF THE DIFFERENT UNITS AND SYSTEMS

SAFETY

RISK ANALYSIS ASSESSMENT (HAZOP METHODOLOGY) TO BE PERFORMED TO IMPROVE SAFETY AND OPERABILITY OF THE PROCESS. SAFETY INSTRUMENTED SYSTEMS (SIS) WILL FULLFIL REQUIREMENTS OF FUNCTIONAL SAFETY STANDARDS

MONITORING

COMPREHENSIVE AND ADVANCED IN-FURNACE MONITORING OF THE COMBUSTION AND CO_2 CAPTURE PROCESSES

PLANT AUXILIARIES

SOME TO BE PROVIDED FROM ADJACENT COMPOSTILLA P. S. (ca. 1200 MW), OWNED BY THE SPANISH UTILITY ENDESA

PLANT CONFIGURATION

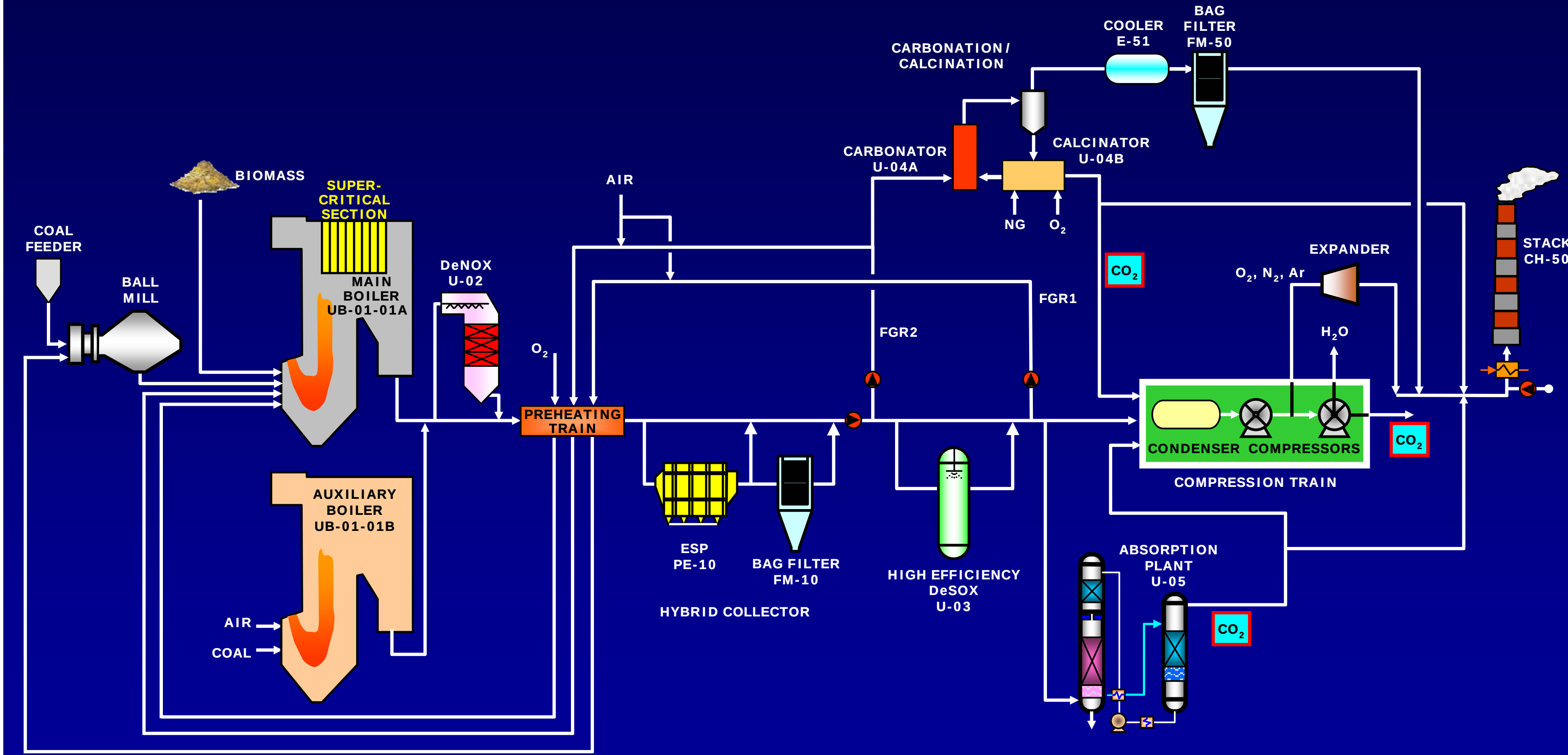
SECTIONS

1. FUEL PREPARATION SYSTEM
2. COMBUSTION SECTION
3. FLUE GAS RECYCLE – AIR / FGR / O_2 PREHEATING
4. FLUE GAS CLEANING SECTION
5. CO_2 CAPTURE
6. UTILITIES AND AUXILIARY UNITS

FUNDACIÓN CIUDAD DE LA ENERGÍA

PROCESS DIAGRAM

EL BIERZO FACILITY FOR CO_2 ABATEMENT AND CAPTURE



FUNDACIÓN CIUDAD DE LA ENERGÍA

FUEL PREPARATION SYSTEM

EL BIERZO FACILITY FOR CO_2 ABATEMENT AND CAPTURE

- ✓ SUITABLE FOR A WIDE RANGE OF COALS FROM ANTHRACITE TO LIGNITE
- ✓ DESIGN COAL: ANTHRACITE (MEDIUM-HIGH VOLATILE COALS FOR STARTING-UP OF THE EXPERIMENTAL PROGRAMME)
- ✓ INDIRECT COMBUSTION SYSTEM
- ✓ MILL INLET GAS TEMPERATURE RANGE: 250 - 300 ºC
- ✓ BIOMASS OXYCOMBUSTION: TO BE CONSIDERED IN PHASE II

COMBUSTION SECTION (I)

- ✓ TWO PULVERIZED COAL COMBUSTORS WITH SAME THERMAL INPUT:
  - ➢ OXY-FUEL COMBUSTOR (4 MW_{TH}): OXYGEN RANGE FROM AIR COMBUSTION TO OXY-FUEL COMBUSTION
  - ➢ AUXILIARY COMBUSTOR (4 MW_{TH}): ONLY FOR AIR COMBUSTION
- ✓ U TYPE FURNACES TO ACHIEVE LONG RESIDENCE TIME AND ENSURE CARBON BURNOUT (UP TO 5 SECONDS ABOVE 1,200 ºC)
- ✓ DOWNFIRED LOW NO_X BURNERS WITH VARIABLE SWIRL CAPACITY FOR ALL THE INCOMING STREAMS
- ✓ FOUR DIFFERENT STREAMS TO THE OXY-FUEL BURNER

  PRIMARY, SECONDARY, TERTIARY AND OXYGEN

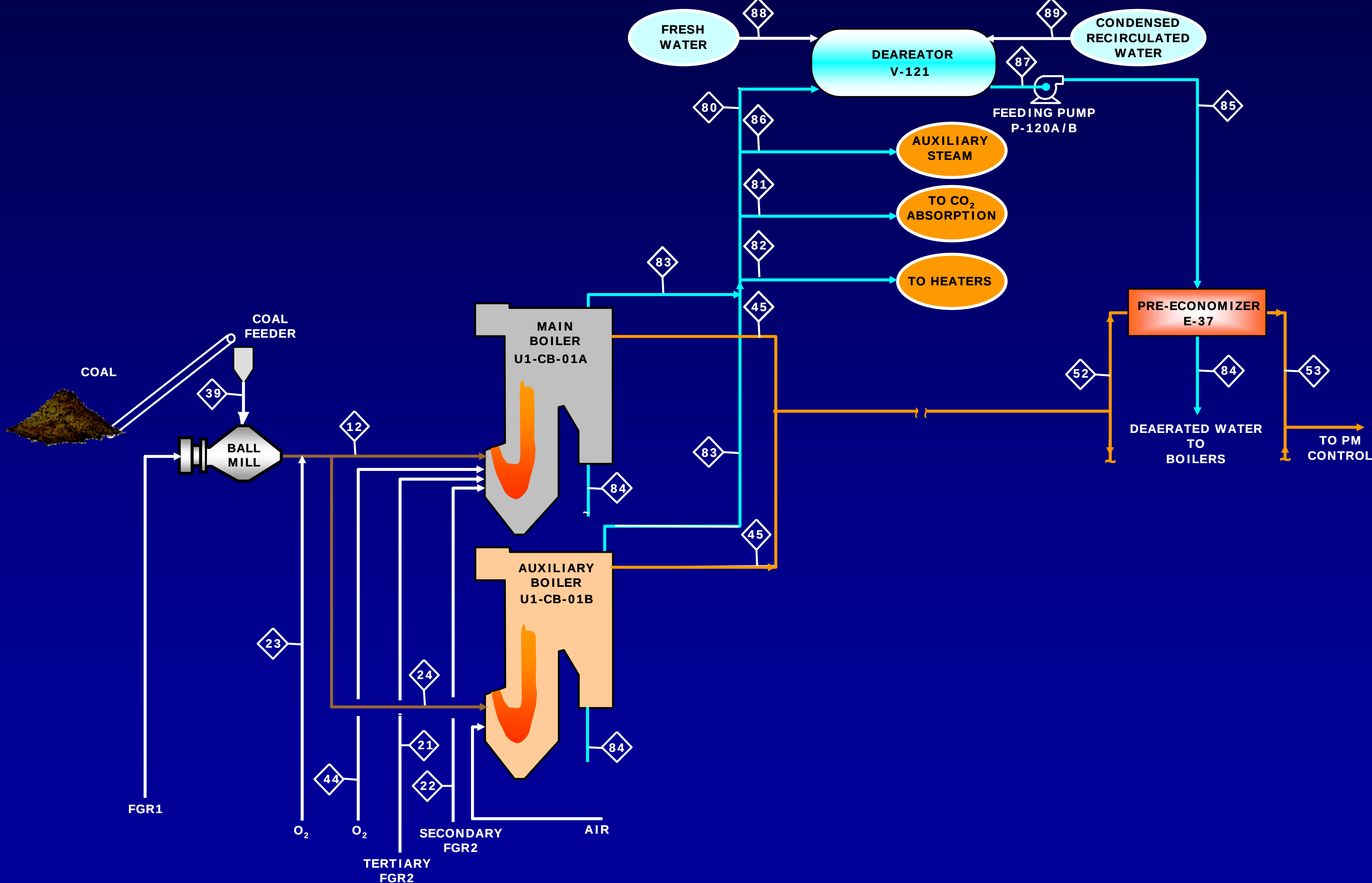
COMBUSTION SECTION (II)

- ✓ ACCESS POINTS IN FINAL FURNACE SECTIONS FOR MATERIALS TESTING BOTH AT SUB AND SUPERCRITICAL CONDITIONS
- ✓ COMPREHENSIVE PORT ARRAYS ALONG THE COMBUSTORS TO FACILITATE IN-FURNACE COMBUSTION MONITORING
- ✓ STEAM PARAMETERS: 10 BAR, 250 ºC
- ✓ STEAM WILL BE USED FOR IN-HOUSE PROCESSES WHEREVER POSSIBLE:
  - CO_2 SCRUBBING PROCESS
  - AUXILIARY STEAM HEATERS
  - PRODUCTION OF LOW PRESSURE STEAM

FUNDACIÓN CIUDAD DE LA ENERGÍA

COMBUSTION SECTION PROCESS DIAGRAM

EL BIERZO FACILITY FOR CO_2 ABATEMENT AND CAPTURE



Prof. Dr. V. J. Cortes

FLUE GAS RECYCLE – AIR / FGR / O_2 PREHEATING TRAIN (I)

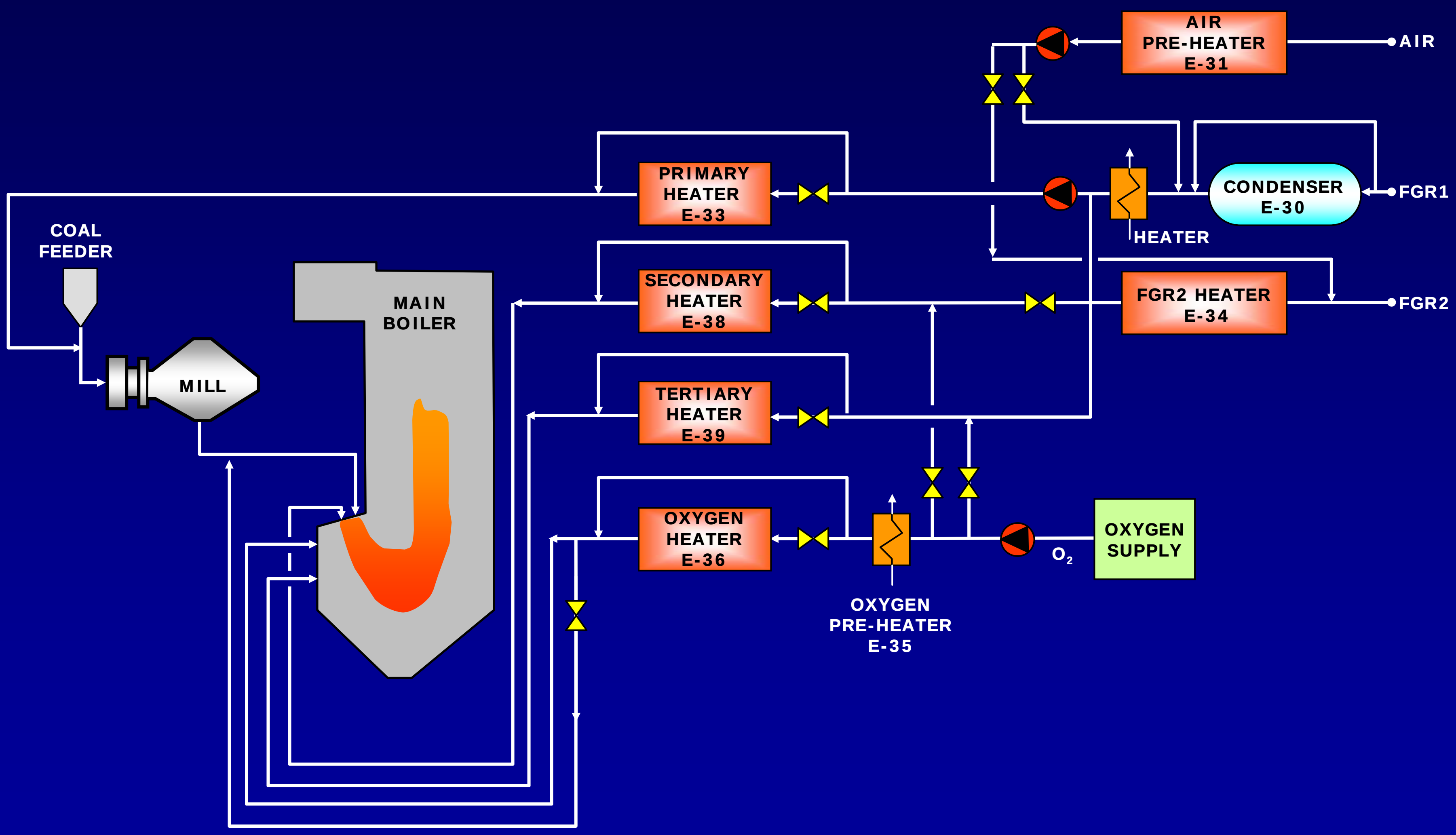
- ✓ FLUE GAS RECIRCULATION LEVEL: 65% - 75% OF TOTAL GASES THROUGH THE BOILER
  - ➢ FGR1 PRIMARY STREAM EXTRACTION, T = 50 - 80 ºC, AFTER SO_X REMOVAL
  - ➢ FGR2 SECONDARY AND TERTIARY STREAM EXTRACTION.

    T = 200 ºC, BEFORE SO_X REMOVAL
- ✓ SPECIAL ATTENTION TO RECIRCULATION BOOSTERS AND FANS LOCATIONS: TEMPERATURE LEVELS AND ACID DEW POINT RESTRICTIONS
- ✓ O_2 IN PRIMARY, SECONDARY AND TERTIARY STREAMS LIMITED TO 23% (w.b.) FOR SAFETY REASONS. O_2 BALANCE FED DIRECTLY TO THE BURNER

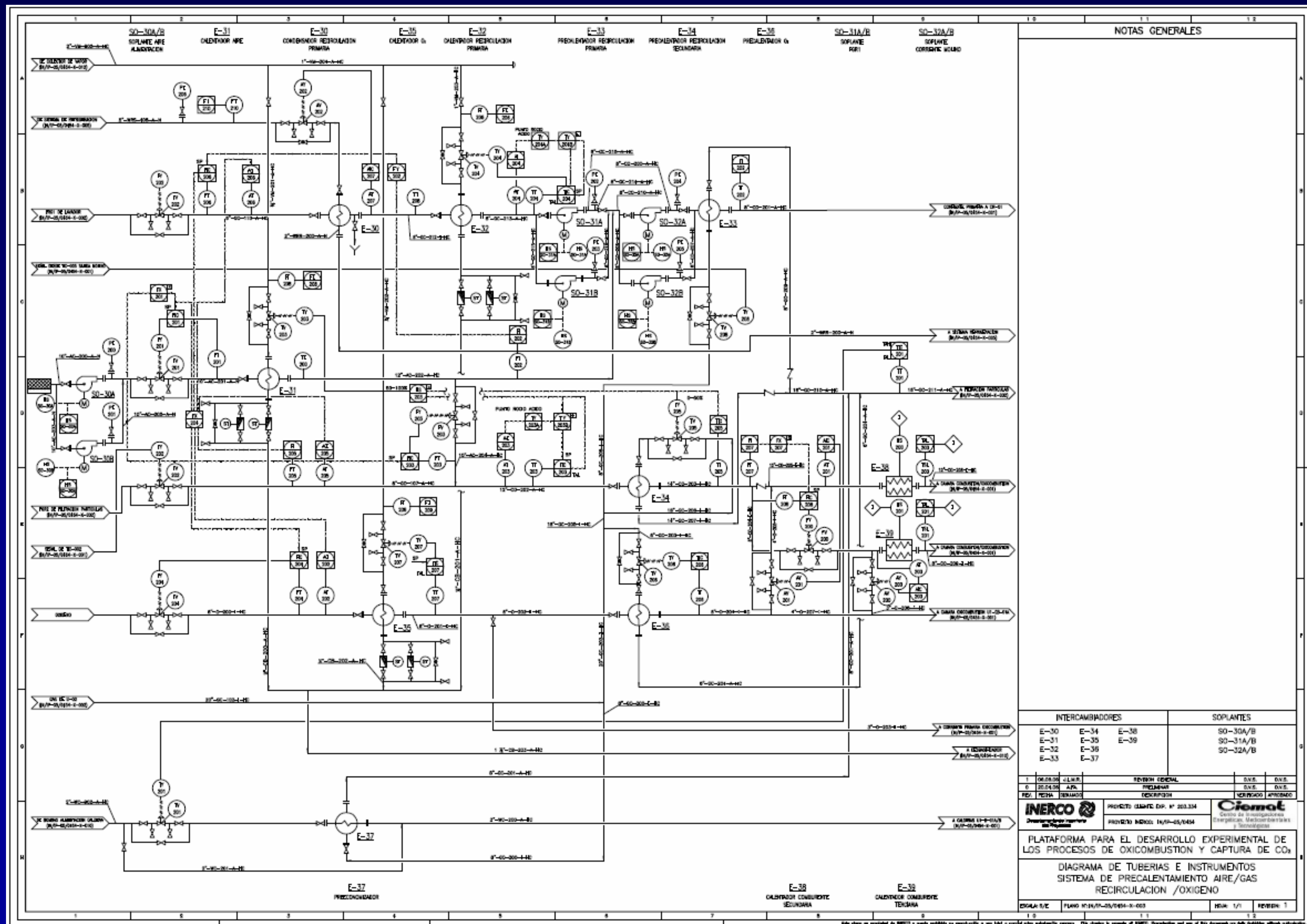
FLUE GAS RECYCLE – AIR / FGR / O_2 PREHEATING TRAIN (II)

- ✓ FULLY INTEGRATED PREHEATING TRAIN ADAPTABLE TO ANY OPERATING SCENARIO (FROM AIR-FUEL TO OXY-FUEL COMBUSTION)
- ✓ PREHEATING TEMPERATURE INTERVALS:
  - PRIMARY STREAM: 250 - 300 ºC
  - SECONDARY AND TERTIARY STREAMS: 200 - 350 ºC
  - O_2 STREAM: 200 - 350 ºC
- ✓ ADDITIONAL HEATING CONTROL THROUGH STEAM HEATERS AND BYPASS DUCTS
- ✓ GAS BURNERS FOR START-UP TIME REDUCTION

AIR / FGR / O_2 PREHEATING TRAIN PROCESS DIAGRAM



P&I AIR / FGR / O_2 PREHEATING TRAIN



FLUE GAS CLEANING SECTION (I)

- ✓ SELECTIVE CATALYTIC REDUCTION (SCR)
- ✓ SIZED TO COMPLEMENT NO_X REDUCTION OBTAINED BY PRIMARY MEASURES AND LOW NO_X BURNERS
  - ➢ GAS PRE-CONDITIONING: DUST PRE-SEPARATOR + GAS COOLER
- ✓ SCR DESIGN SPECIFICATIONS
  - ➢ GAS FLOW: 4,500÷3,250 Nm^3/h
  - ➢ INLET NO_X: 1,660÷2,000 mg/Nm^3
  - ➢ OUTLET NO_X: max. 20 PPMV

FLUE GAS CLEANING SECTION (II)

✓ **PARTICULATE CONTROL**

- **HYBRID COLLECTOR: ELECTROSTATIC PRECIPITATOR + BAG FILTER, LAY-OUT FOR INDEPENDENT OR JOIN OPERATION**
- **DESIGN SPECIFICATIONS**
  - **GAS FLOW: 4,500÷3,250 Nm^3/h**
  - **INLET DUST LOAD: 40÷56 g/Nm^3 (OR 8÷11.5 WITH DUST PRE-SEPARATOR)**
  - **OUTLET DUST LOAD: <15 mg/Nm^3 (CO_2 CAPTURE REQUIREMENT)**

FLUE GAS CLEANING SECTION (III)

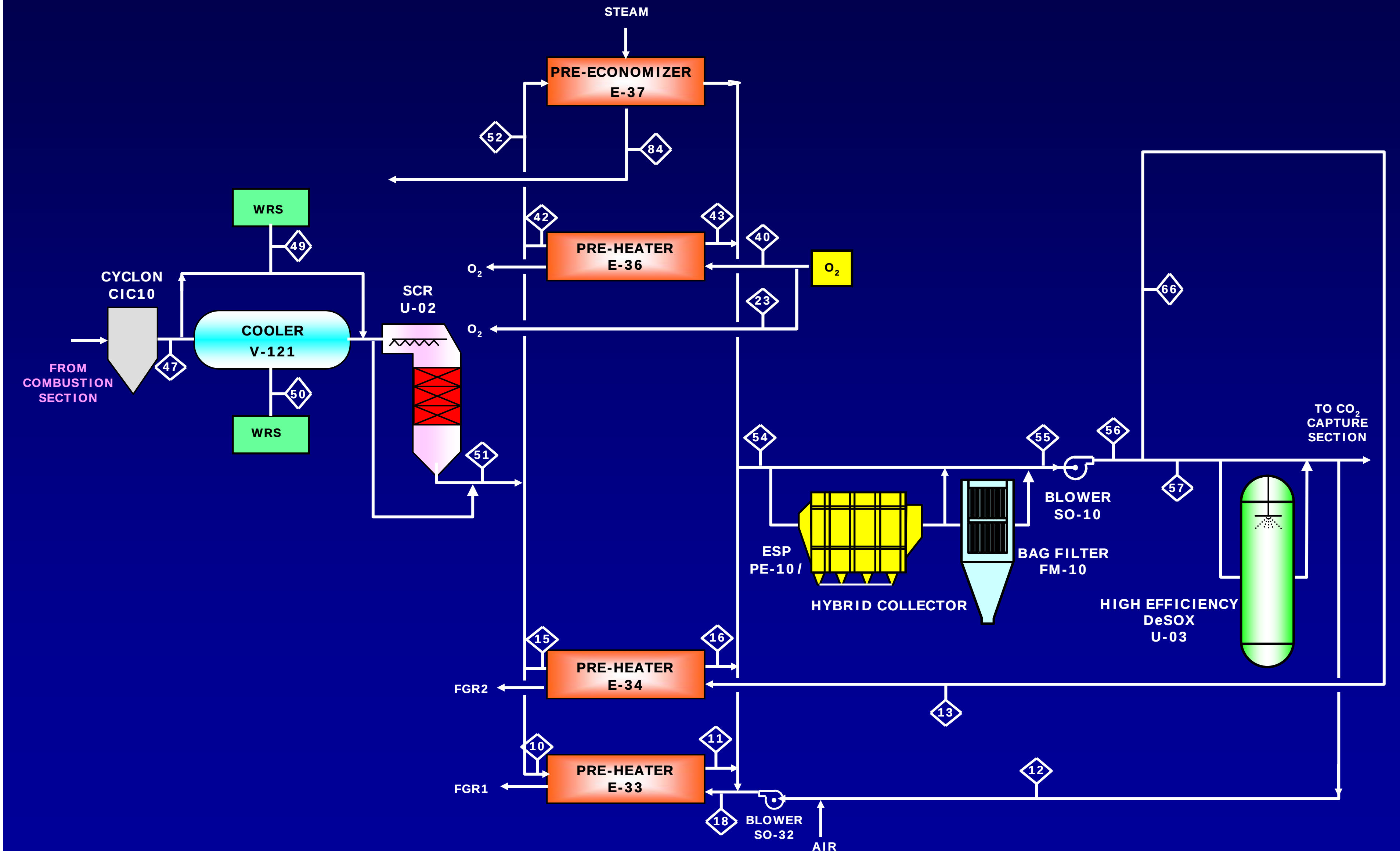
✓ WET SCRUBBER

- VERY HIGH EFFICIENCY FGD SCRUBBER USING LIME/LIMESTONE. DUE TO LOW REACTIVITY OF LOCAL LIMESTONES AND SO_2 REMOVAL EFFICIENCY REQUIRED
- DESIGN SPECIFICATIONS
  - GAS FLOW: 4,500÷3,250 Nm^3/h
  - INLET SO_2: 4,015÷6,550 mg/Nm^3
  - OUTLET SO_2: <30 mg/Nm^3 (CO_2 CAPTURE REQUIREMENT)
- OXYGEN-INDUCED SULPHITE OXIDATION, TO ELIMINATE A SOURCE OF AIR INGRESS
- ASSOCIATED SORBENT STORAGE AND PREPARATION UNITS

FLUE GAS CLEANING SECTION PROCESS DIAGRAM

FUNDACIÓN CIUDAD DE LA ENERGÍA

EL BIERZO FACILITY FOR CO_2 ABATEMENT AND CAPTURE



Prof. Dr. V. J. Cortes

CO_2 CAPTURE SECTION (I)

- ✓ CO_2 CAPTURE TECHNOLOGIES CONSIDERED:
  1. **CHEMICAL ABSORPTION:** FOR AIR-FUEL AND LOW OXYGEN ENRICHED COMBUSTION (UP TO 40% O_2 PARTIAL OXY-COMBUSTION) DESIGNED FOR AN ALIQUOT OF THE TOTAL FLUE GAS
  2. **FLUE GAS COMPRESSION:** FOR FULL OXY-COMBUSTION AND HIGH OXYGEN ENRICHED COMBUSTION (OVER 60% O_2 PARTIAL OXY-COMBUSTION)
  3. **CARBONATION/CALCINATION:** FOR AIR-FUEL COMBUSTION, PROCESSING AN ALIQUOT OF TOTAL FLUE GAS (1 MW_{th})

- ✓ CHEMICAL ABSORPTION
  - ➢ **DESIGN SPECIFICATIONS**
    - **GAS FLOW:** 800÷600 Nm^3/h
    - **INLET GAS TEMPERATURE:** 50°C
    - **INLET CO_2:** 15÷30% v/v

CO_2 CAPTURE SECTION(II)

✓ FLUE GAS COMPRESSION

- DESIGN SPECIFICATIONS
  - GAS FLOW: 1,450÷850 Nm^3/h
  - INLET GAS TEMPERATURE: 50°C
  - INLET CO_2: 48÷80% v/v

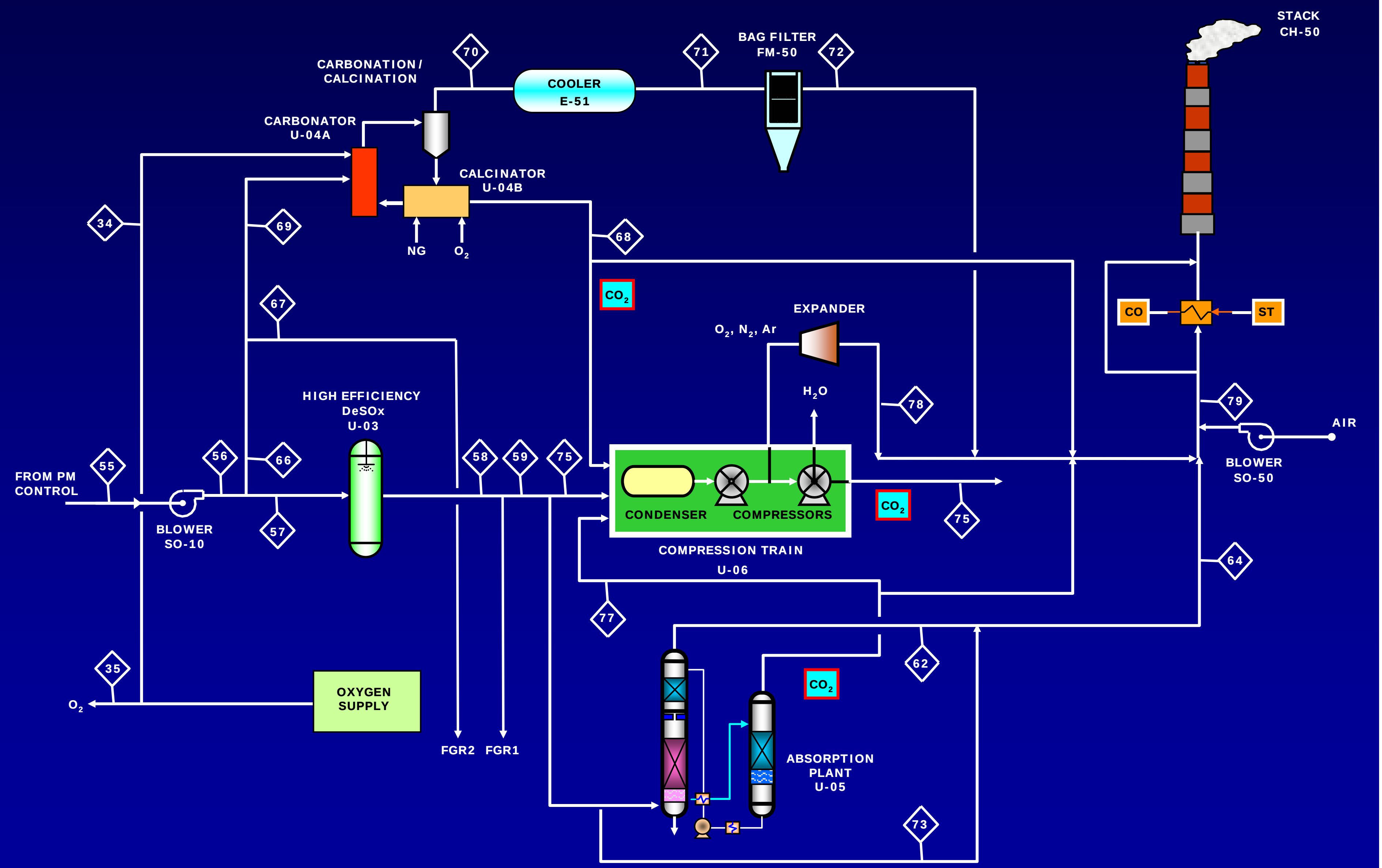
✓ CARBONATION/CALCINATION

- DESIGN SPECIFICATIONS
  - GAS FLOW: 1,130 Nm^3/h
  - INLET GAS TEMPERATURE: 200°C
  - INLET CO2: 15% v/v
  - INLET SO2: 4,015 mg/Nm^3
  - AUXILIARY FUEL: NATURAL GAS
- ADDITIONAL GAS COOLER AND PARTICULATE MATTER CONTROL UNIT REQUIRED

FUNDACIÓN CIUDAD DE LA ENERGÍA

CO_2 CAPTURE PROCESS DIAGRAM

EL BIERZO FACILITY FOR CO_2 ABATEMENT AND CAPTURE

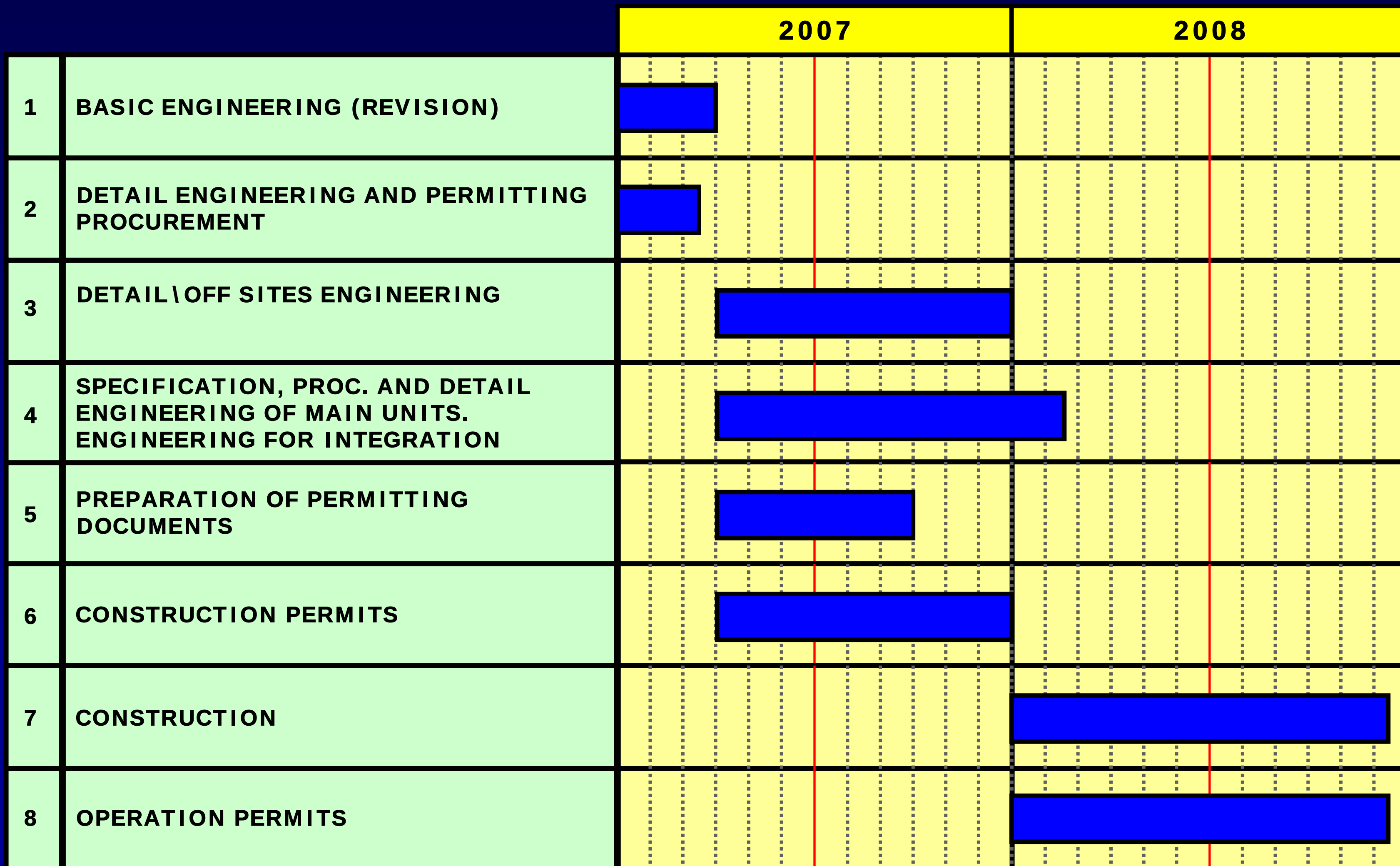


Prof. Dr. V. J. Cortes

UTILITIES AND AUXILIARY UNITS

- ✓ COAL STORAGE AND HANDLING
- ✓ STACK AND FLUE GAS EXHAUSTING SYSTEM
- ✓ STEAM / CONDENSATE TREATMENT UNIT
- ✓ ELECTRICITY SUPPLY
- ✓ WATER SUPPLY UNITS (RAW, TREATED, COOLING, FIRE FIGHTING)
- ✓ COMPRESSED AIR SUPPLY
- ✓ AUXILIARY FUELS UNITS
- ✓ NITROGEN SUPPLY
- ✓ AMMONIA STORAGE AND SUPPLY

TIME SCHEDULE



THE WAY FORWARD (I)

1. REVISION OF BASIC ENGINEERING FOLLOWING RECOMMENDATIONS FROM INT'L ADVISORY GROUP

HEIN, OTERO,OTTER,CORTES

- SEPARATE FUEL HANDLING AND PREPARATION
- EMPHASIS ON FURNACE STAGING FOR NO_X REDUCTION
- RAPID INCORPORATION OF ADSORPTION UNIT FOR OXYGEN SUPPLY
- SIZING OF OXYGEN SUPPLY TO CONSIDER SULPHITE OXIDATION
- FGD CONCEPT: HIGH REMOVAL EFFICIENCY NEEDED. SINGLE/DUAL-CONTACT FLOW SCRUBBER WITH LIME/LIMESTONE ? ONE/TWO PASSES?

THE WAY FORWARD(II)

2. NEGOTIATIONS TO ENGAGE REPRESENTATIVES OF THE FULL INDUSTRIAL CHAIN

- EUROPEAN POWER GENERATORS
- EQUIPMENT SUPPLIERS
- TECHNOLOGY PROVIDERS
- FUEL SUPPLIERS
- OTHER CO_2 EMITTERS

3. PARTICIPATION ON THE EC 7th FRAMEWORK PROGRAM

- FIRM ACTIONS FOR THE PROVISION OF A HIGH QUALITY MAJOR RESEARCH FACILITY ALREADY INITIATED

- ROBUST CAPABILITIES FOR EFFICIENCY, AVAILABILITY AND SYSTEMS INTEGRATION STUDIES

FUNDACIÓN "CIUDAD DE LA ENERGÍA"

Test Facility for Advanced Technologies for CO_2 Abatement and Capture in Coal Power Generation El Bierzo

STATE OF DEVELOPMENT

Prof. Dr. Vicente J. Cortés Galeano, Program Manager
Prof. Dr. Benito Navarrete Rubia
School of Engineering
University of Seville. Spain

IEAGHG International Oxy-Combustion Network
2nd Workshop
25th and 26th January 2007
Windsor, CT, USA

Oxy-Fuel Process for Hard Coal with CO_2 Capture

A Part of the ADECOS Project

Funded by the German Federal Ministry of Economic Affairs within the COORETEC program

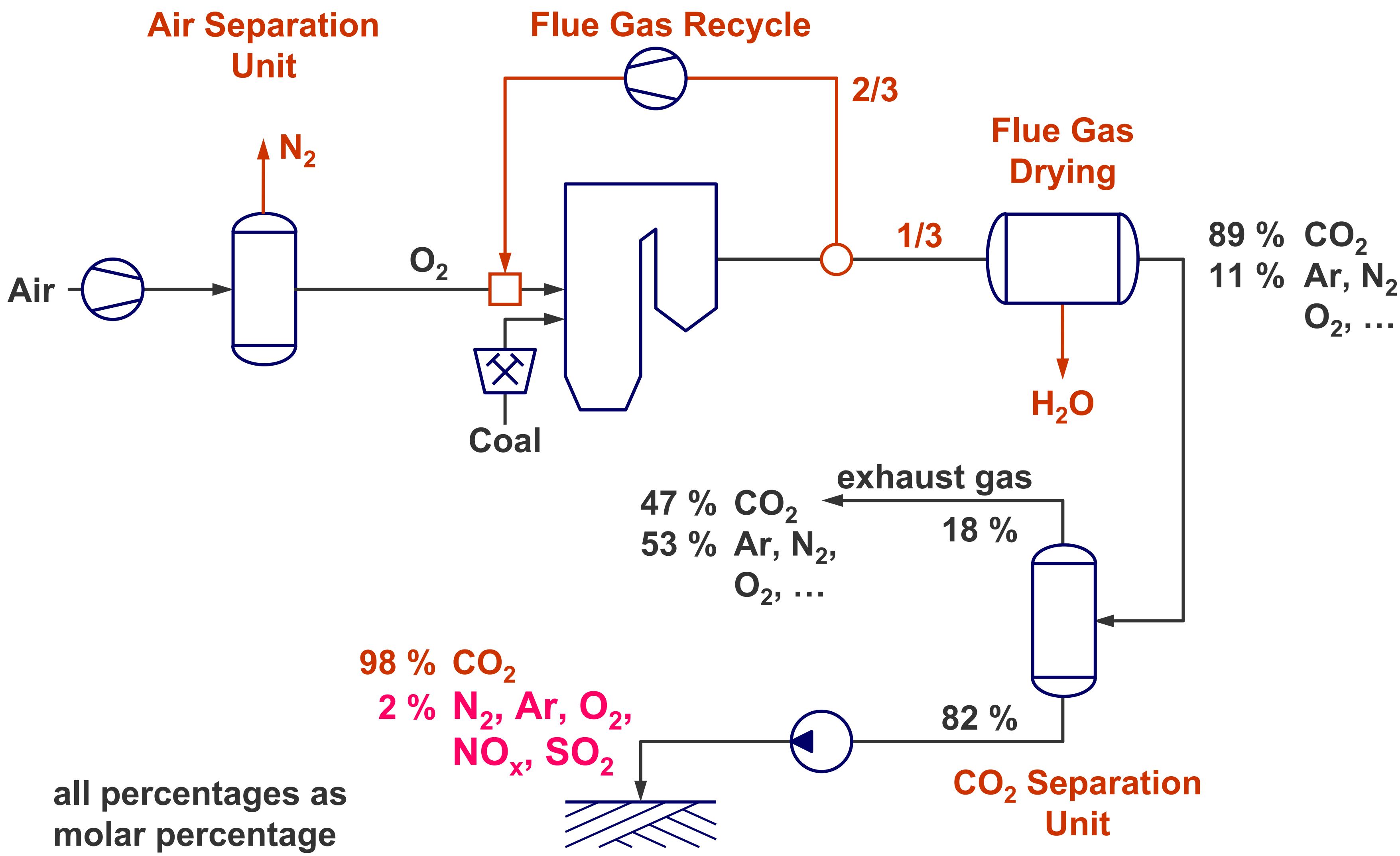
Partners: Vattenfall, ALSTOM, EON, RWE, SIEMENS, Hitachi, TU Dresden, TU Hamburg-Harburg

Presented by

Professor Alfons Kather
Institute of Energy Systems
Hamburg University of Technology
21073 Hamburg, Germany

Oxy-Fuel Process – Simplified Process Scheme

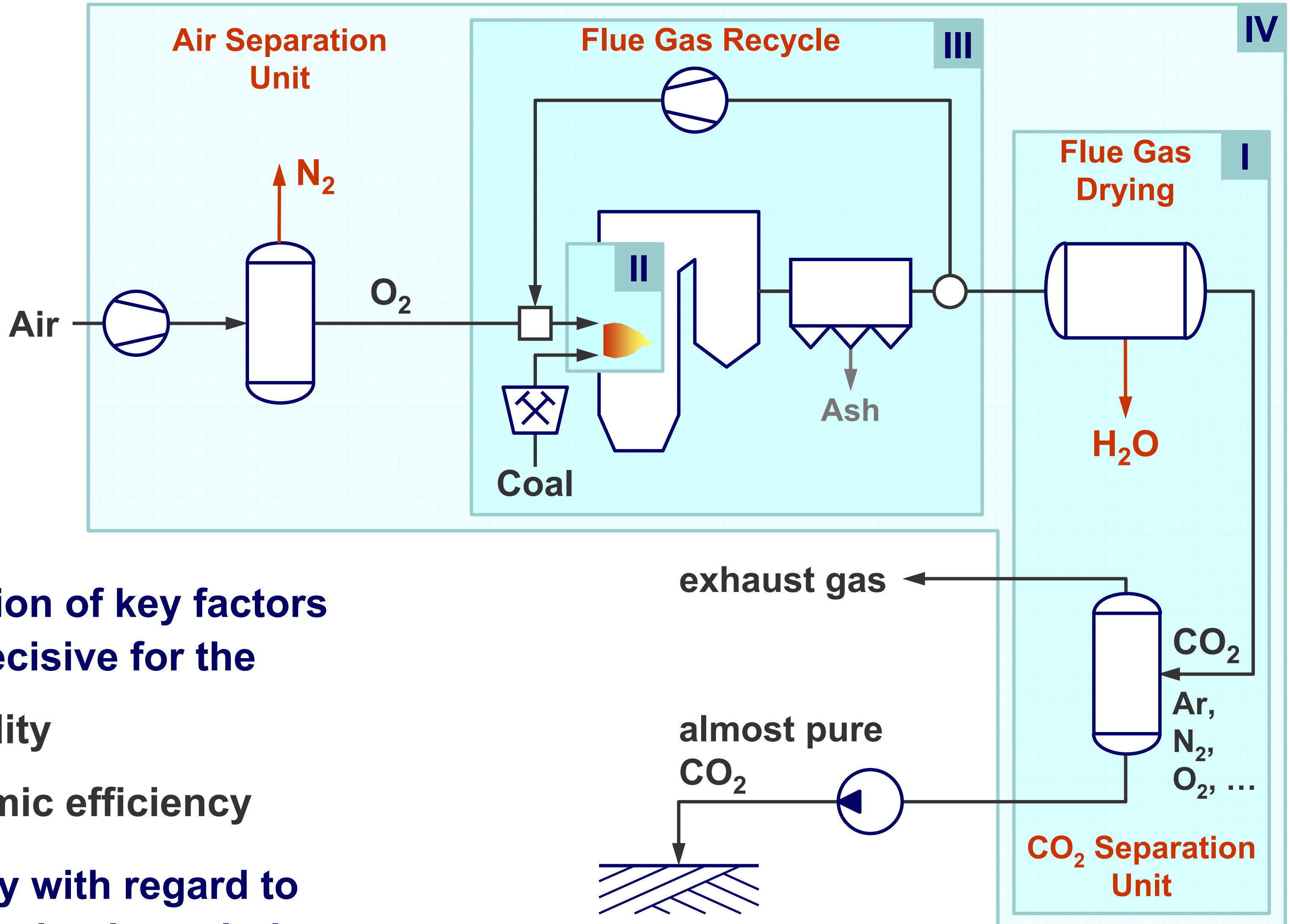
TUHH
Technische Universität Hamburg-Harburg



all percentages as molar percentage

Current Research Projects at the TUHH

TUHH
Technische Universität Hamburg-Harburg



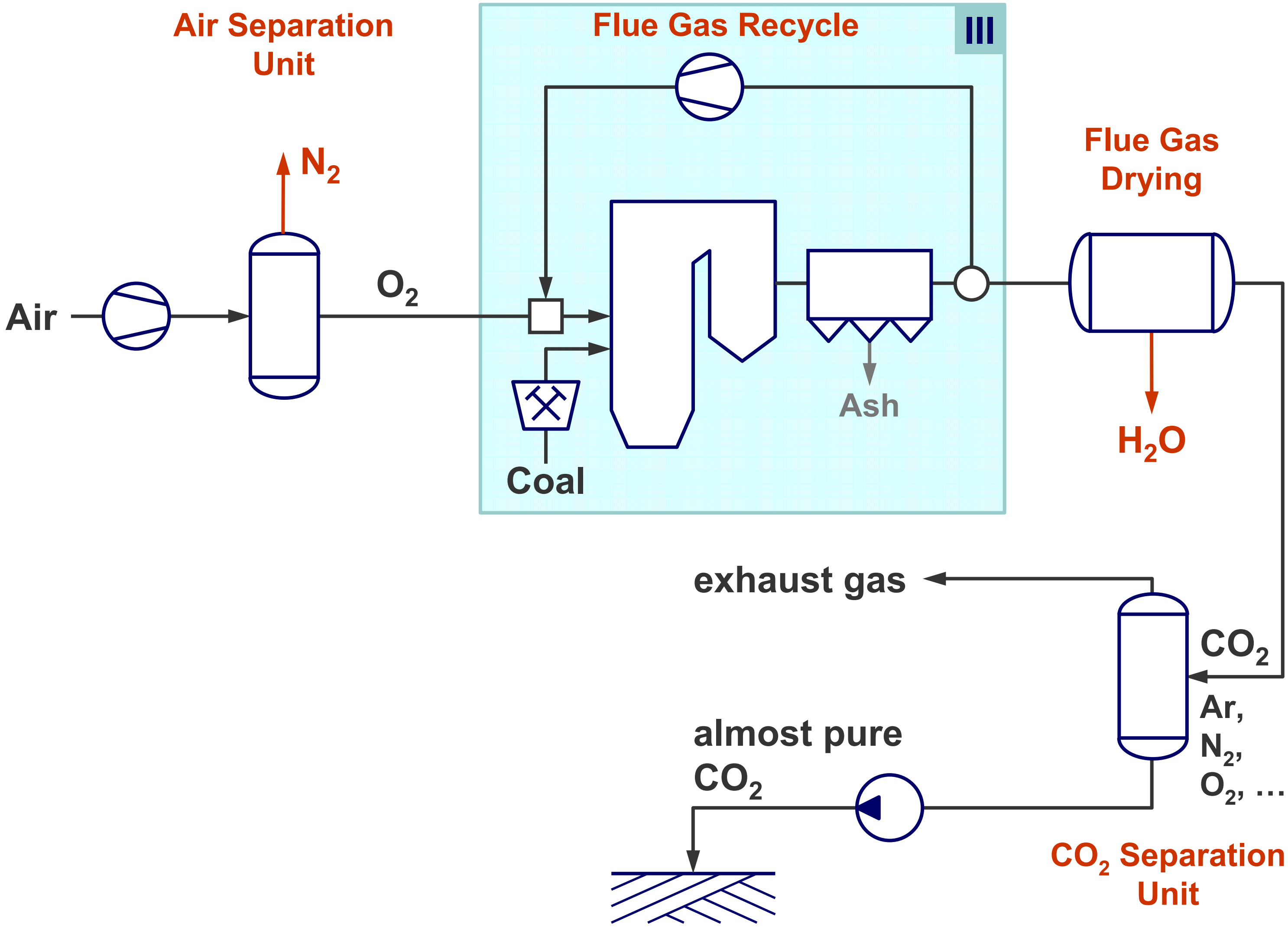
Objective

Identification of key factors that are decisive for the

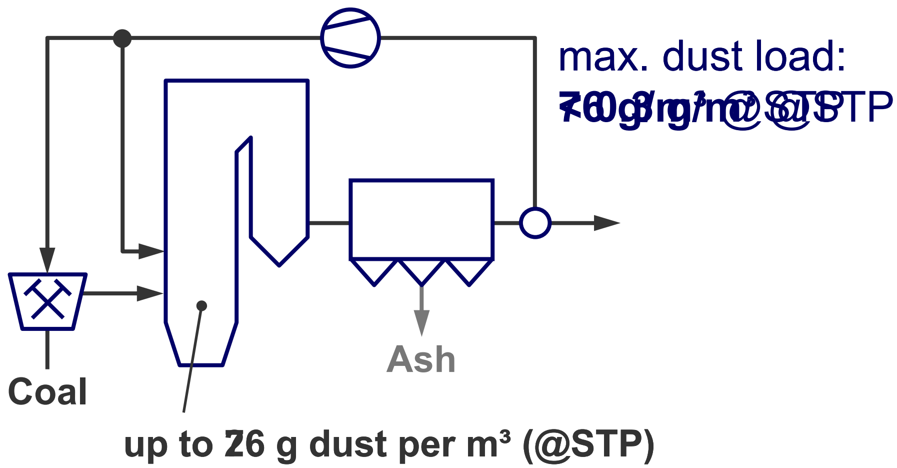
- feasibility
- economic efficiency

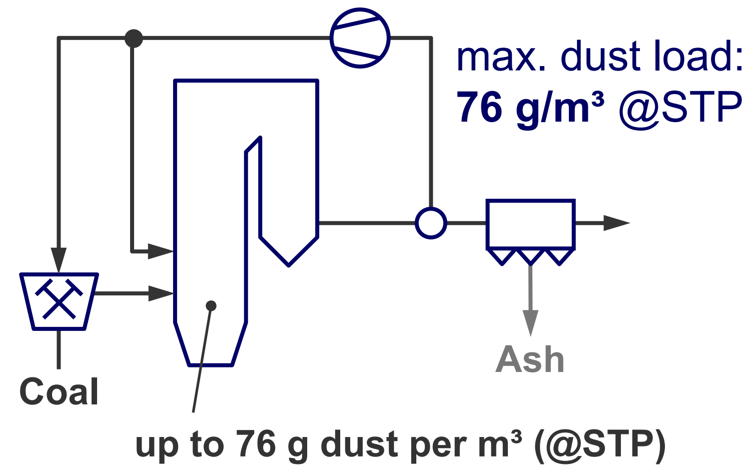
particularly with regard to realistic design boundaries

TUHH
Technische Universität Hamburg-Harburg



Flue Gas Recycle Design Considerations





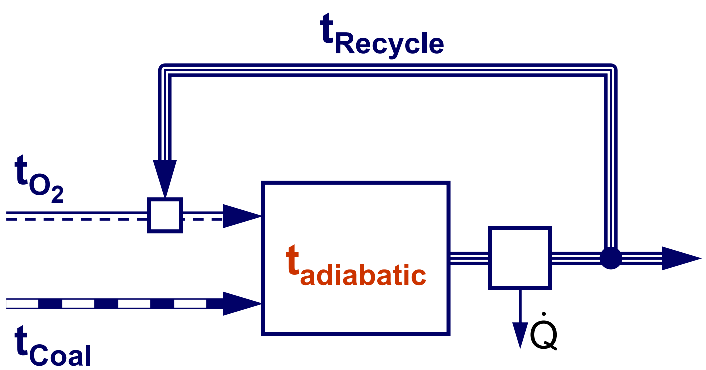
Low-dust recycle

- \+ using high-efficiency axial-flow fan
- – temperature limited to 190 °C,
  270 °C with fixed blades
  - ➡ mill-internal coal drying (300 °C)?
  - ➡ today's feed water temperature at 300 °C ➡ heat sink for cooling?
- – sensitive to load fluctuations (fixed blades)
- – very large dust precipitator and long recycle ducts

High-dust recycle

- – requires low-efficiency radial-flow fan
- \+ more robust than axial-flow fans
- \+ very stable with respect to load fluctuations
- \+ small dust precipitator and short recycle ducts
- • no increased wear of boiler expected
- \+ temperature up to 350 °C possible
  - ➡ mill-internal coal drying

Factors influencing the Recycle Requirement



- **Condition:**

  $t_{adiabatic,\ Air} = t_{adiabatic,\ O_2+Recycle}$

- **Underlying assumptions:**

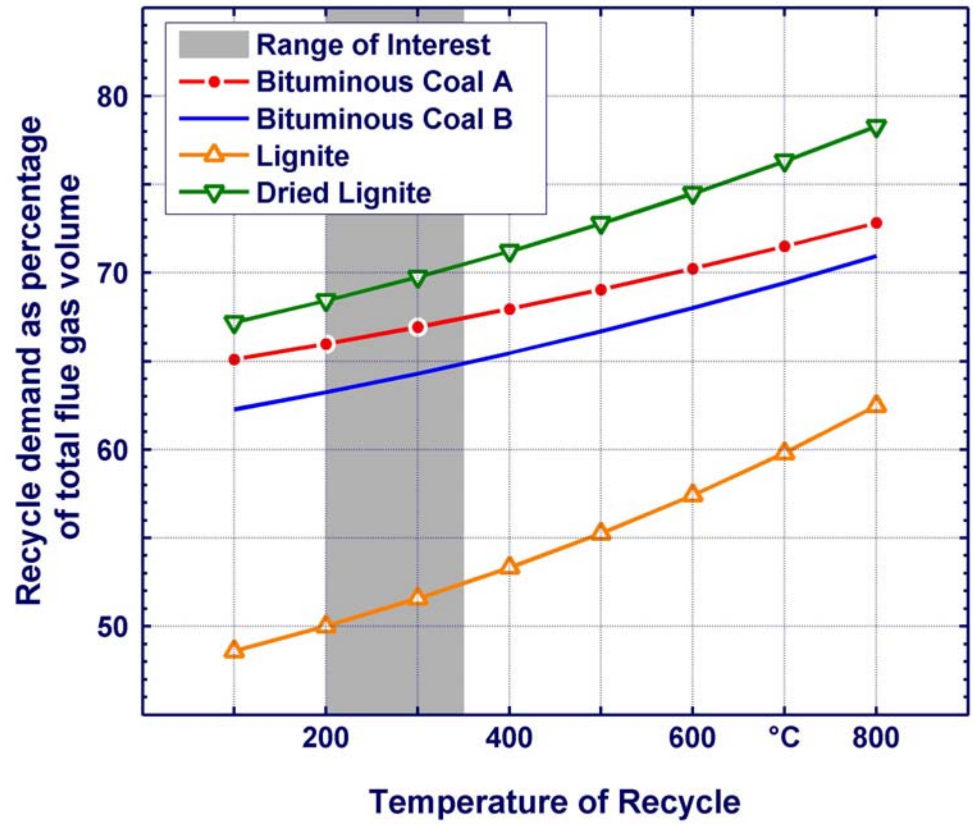
  t_{Air} = 320 °C

  t_{O_2} = 25 °C

  t_{Coal} = 40 °C

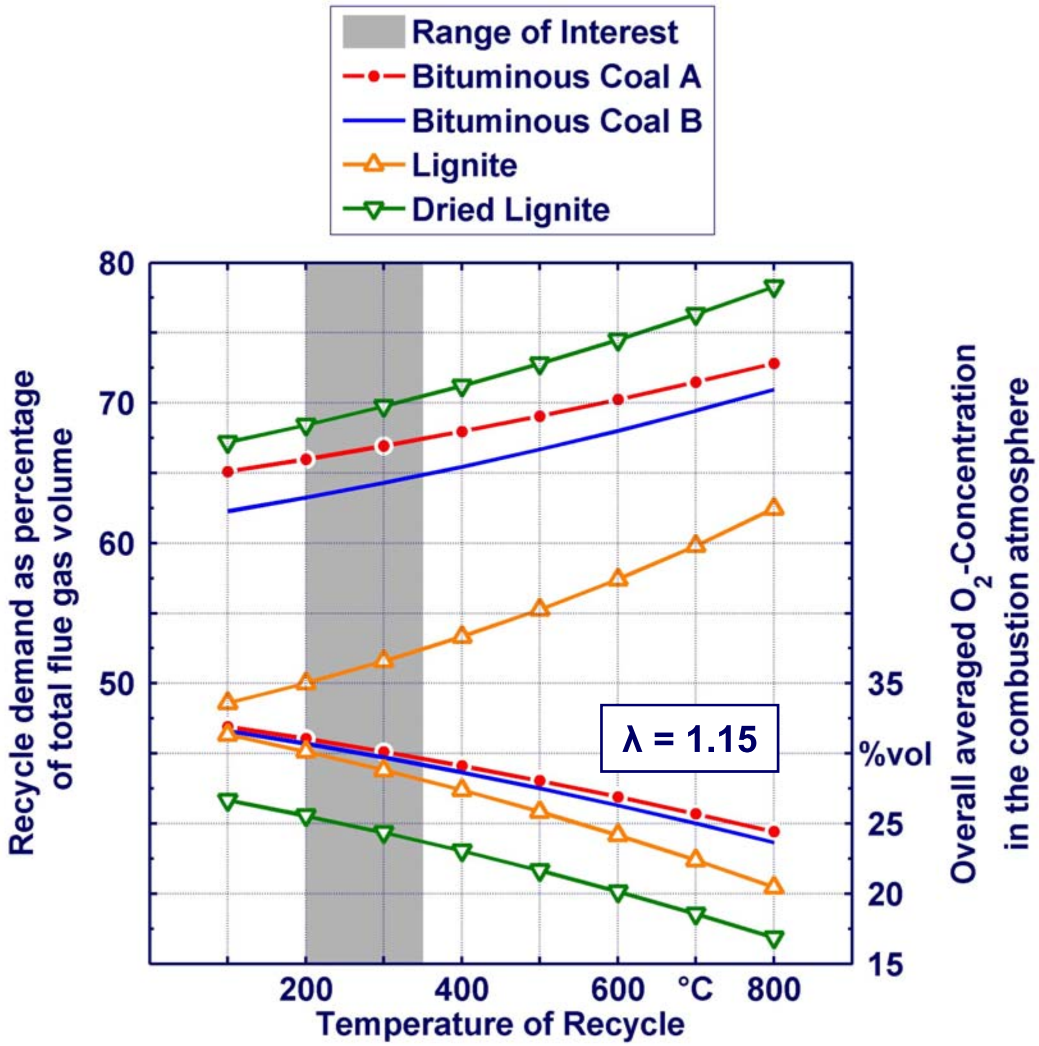
  O_2-excess: 15 %

  O_2-purity: 98 %



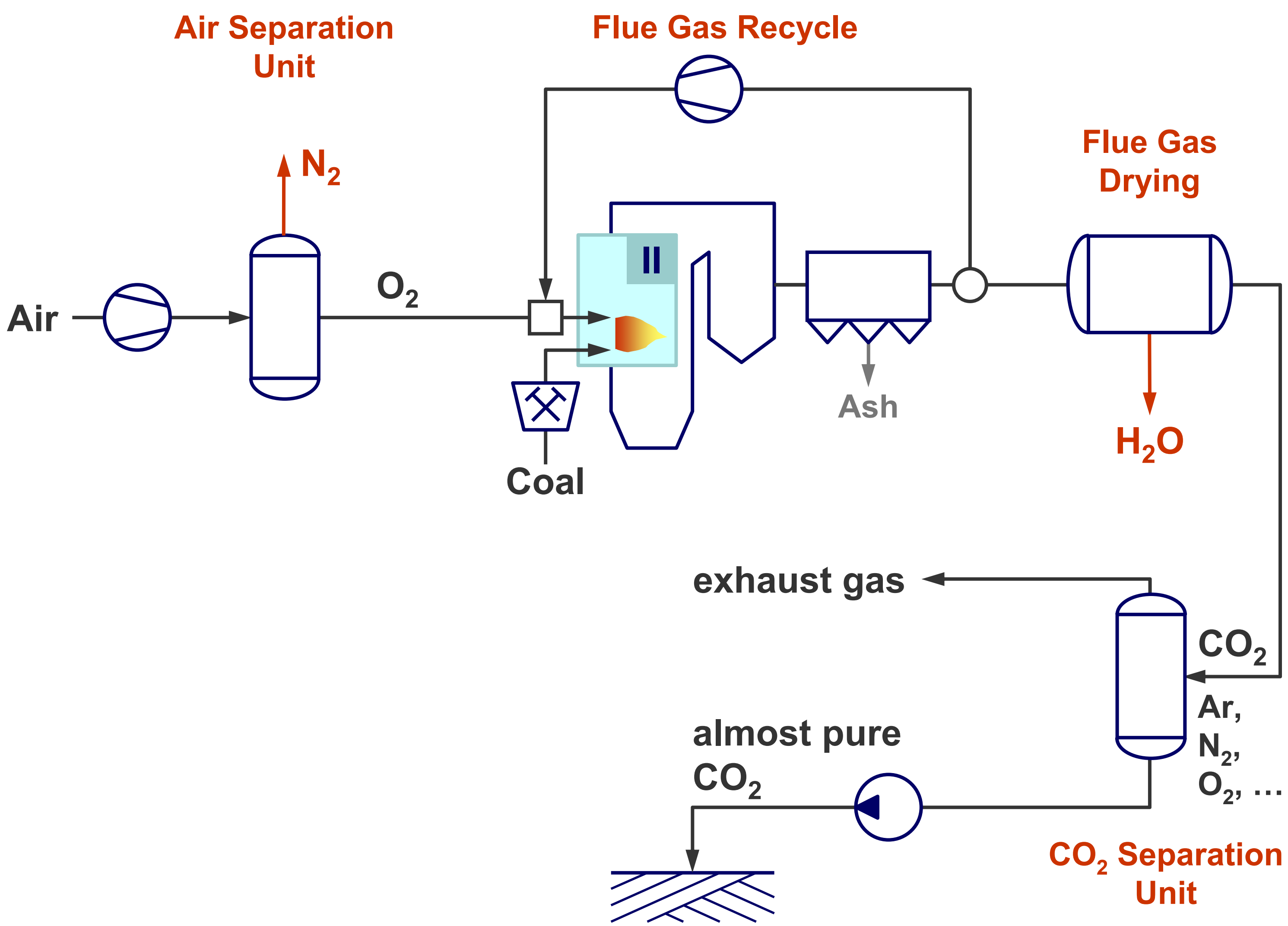
Composition (in % by mass)							NCV	$t_{ad,Air}$
C	H	O	S	N	Ash	H_2O	MJ/kg	°C
65.93	3.63	7.25	0.61	1.58	13.60	7.40	25.40	2126
58.70	4.43	8.82	1.00	1.05	5.00	21.0	22.69	2008

First approach: Oxygen and recycled flue gas are mixed completely prior to the combustion



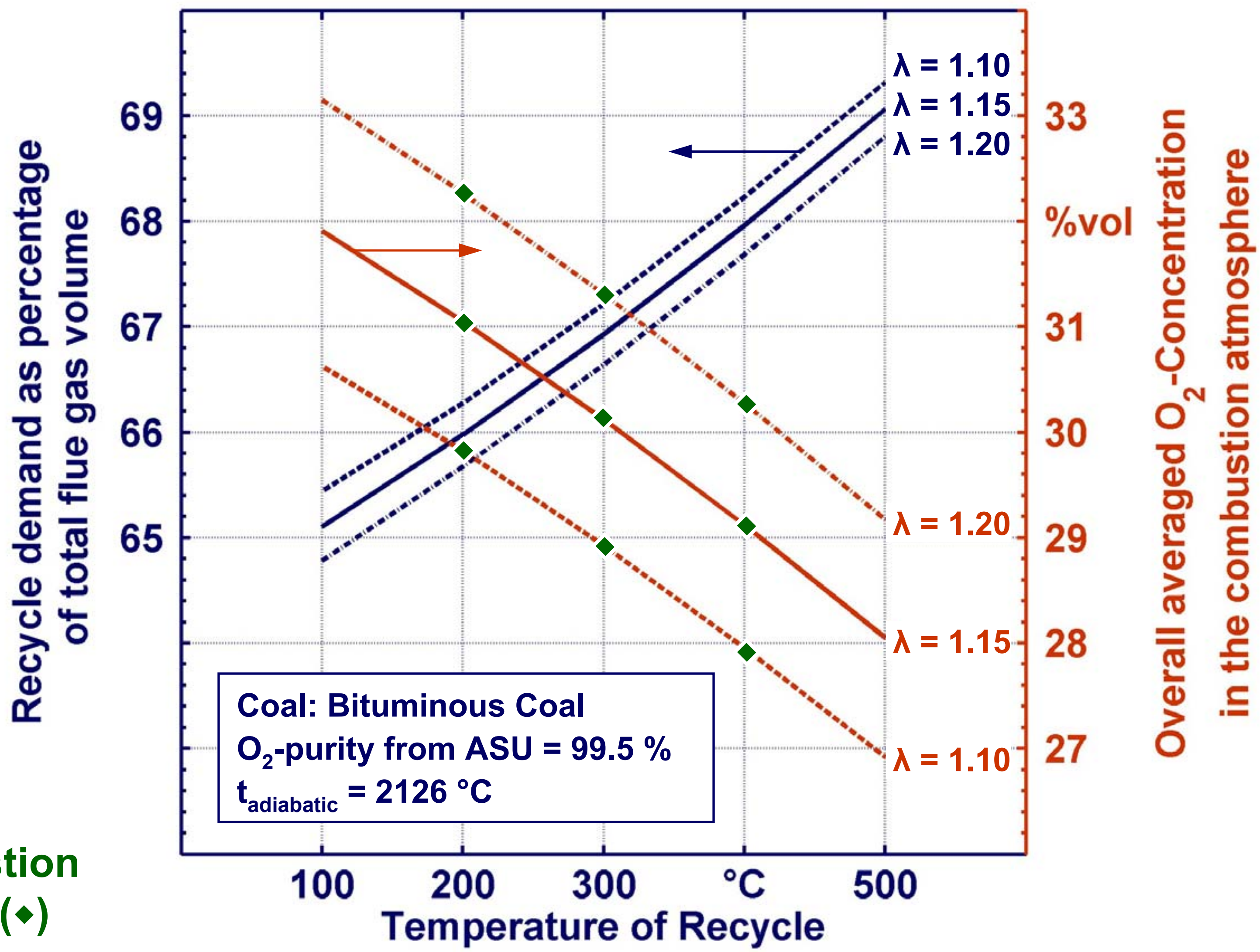
The **oxygen concentration**

- **rises by reducing the recycle,**
- **is always above 21 %vol** (in the range of interest),
- **is a function of both recycle rate and oxygen excess**

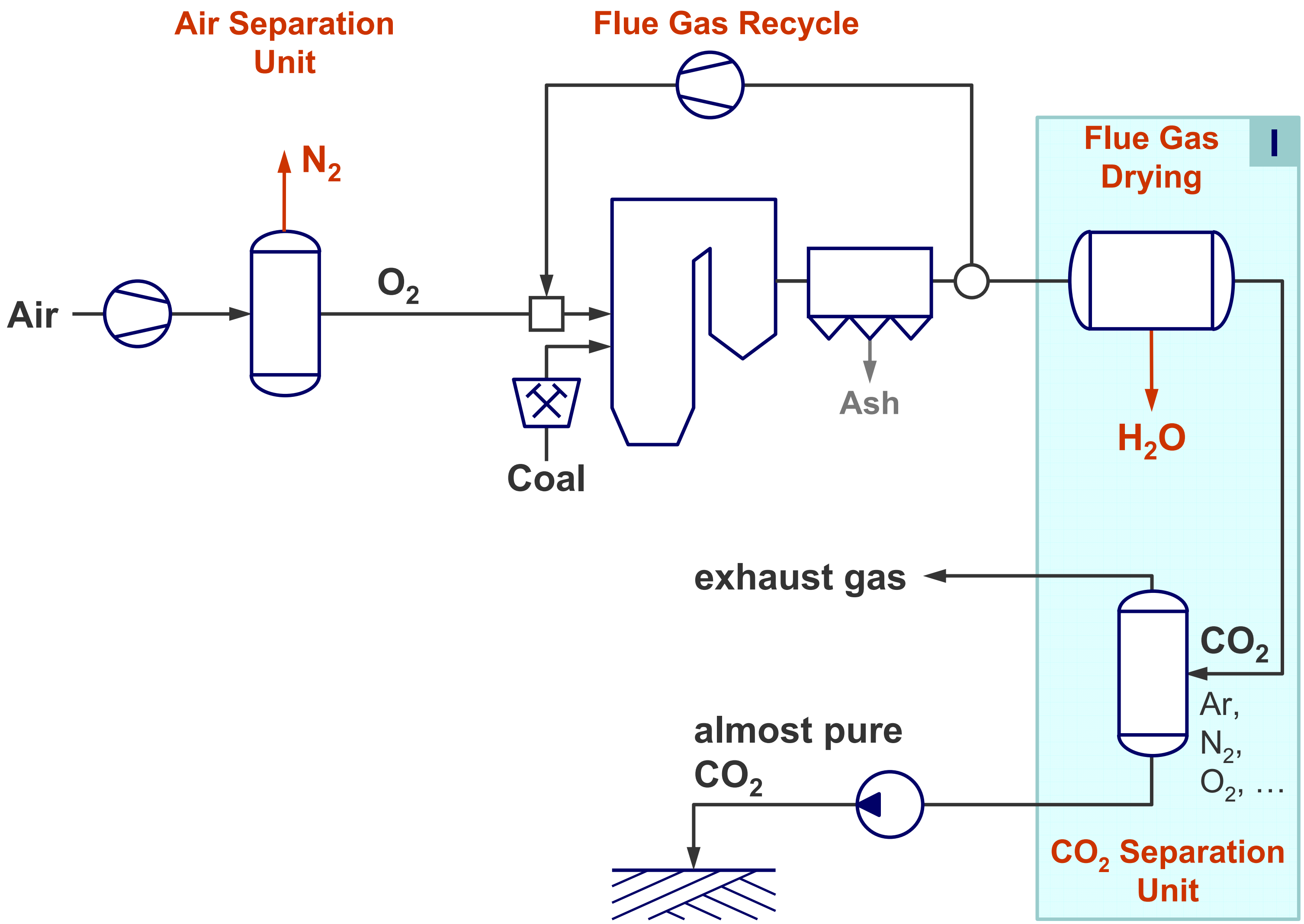

Air Separation Unit
Flue Gas Recycle
Flue Gas Drying
N2
Air
O2
II
Coal
Ash
H2O
exhaust gas
CO2
Ar,
N2,
O2, …
almost pure CO2
CO2 Separation Unit

Oxygen Concentration in the Combustion Atmosphere of the first Combustion Experiments

TUHH Technische Universität Hamburg-Harburg



First combustion experiments (◆)



Air Separation Unit
Flue Gas Recycle
Flue Gas Drying
I
N2
Air
O2
Coal
Ash
H2O
exhaust gas
CO2
Ar,
N2,
O2, …
almost pure CO2
CO2 Separation Unit

Impurities in the Flue Gas

- **O_2, NO_X, SO_2**
  - **They may influence negatively the geological storage of the injected CO_2 by changing transport properties or by causing geochemical reactions**
    - ➡ **The maximum permissible concentrations for these impurities are still to be defined**

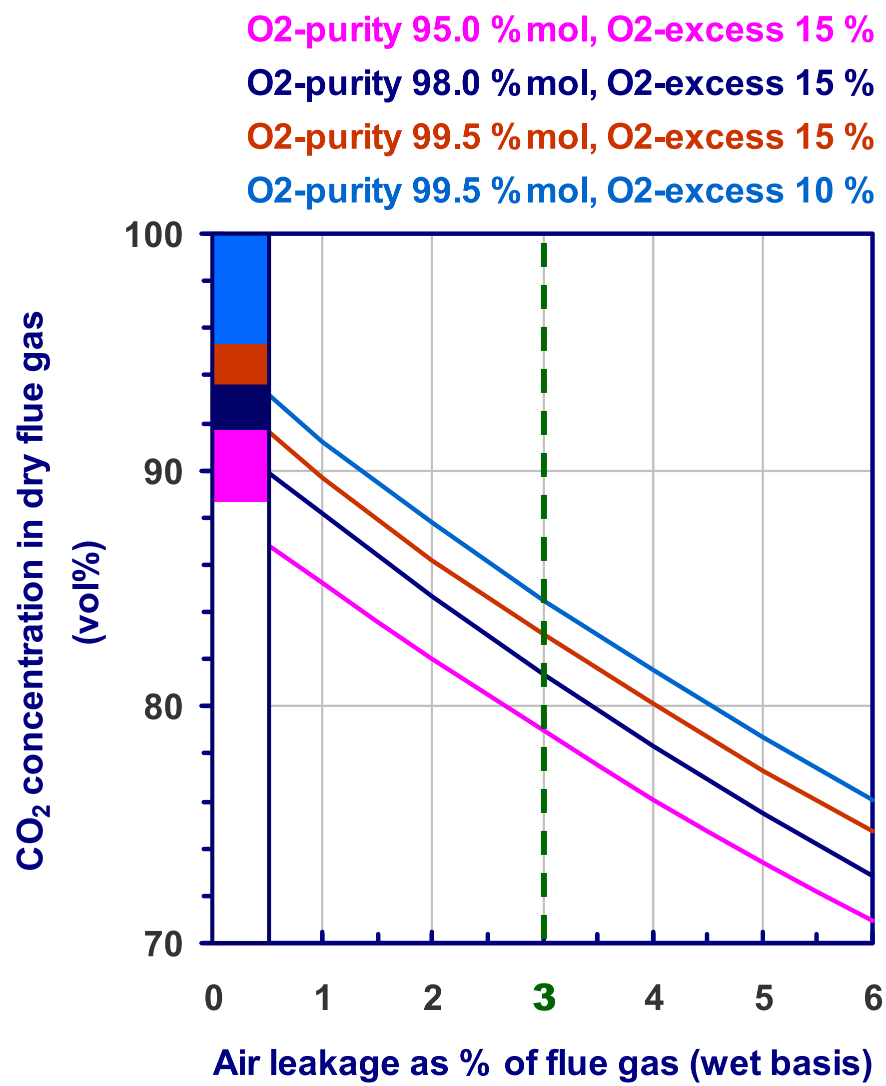
- **N_2, Ar**
  - **They are inert components which have no significant impact underground**
  - **They increase auxiliary power demand during liquefaction of the CO_2** (other impurities cause the same, too)
  - **Removing them during air separation** (to achieve purer O_2) **increases the auxiliary power demand of the air separation unit**
    - ➡ **Need for optimization between air separation and CO_2-liquefaction** (considering also air leakage)

Impact of Impurities on the CO_2-Concentration

TUHH Technische Universität Hamburg-Harburg

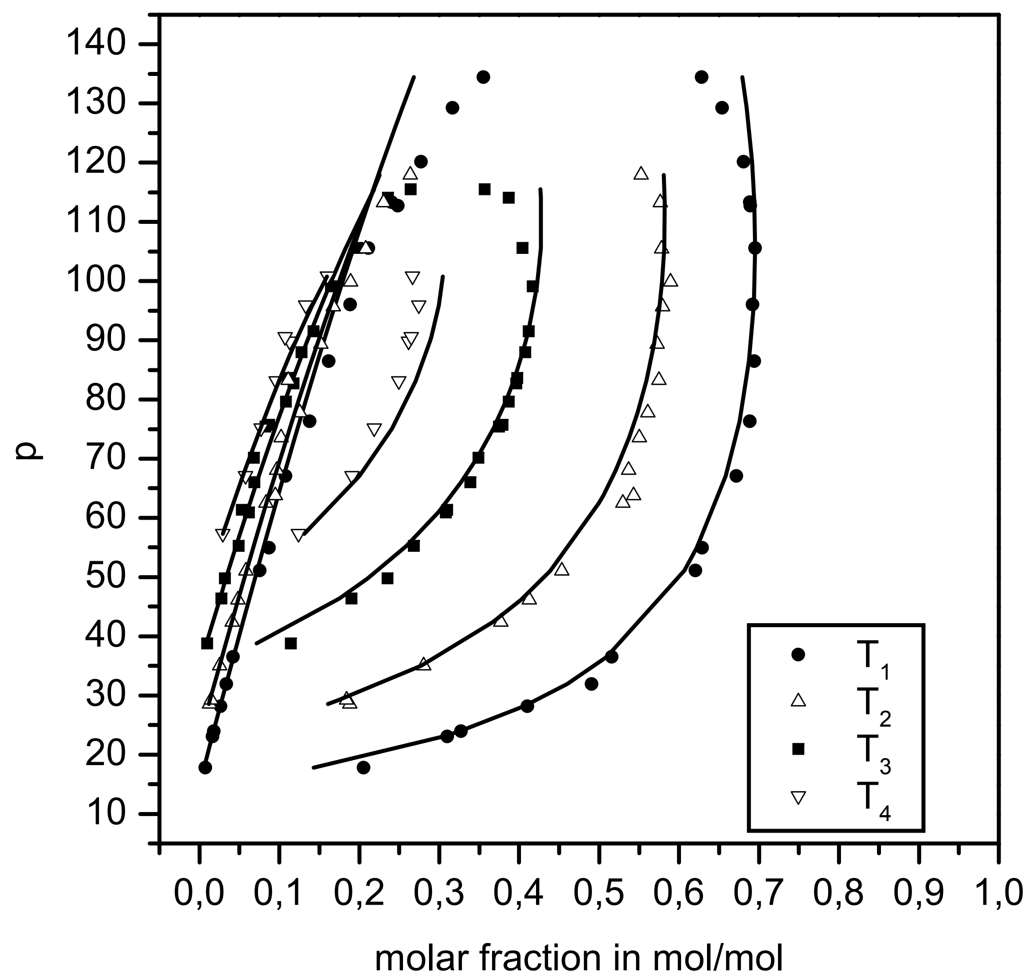
- Fuel's nitrogen and sulfur
- Oxygen excess
  - ➡ 3 – 3.5% / 4.5 – 5% O_2-residue
- Air separation unit
  - ➡ 98% O_2-purity: 2% Ar
  - ➡ 95% O_2-purity: 3.8% Ar + 1.2% N_2
- Air leakage
  - ➡ approx. 3 % of flue gas flow for a new conventional power plant
  - ➡ up to 10 % over the years for power plants in use

➡ **Air leakage is a major source for impurities and needs to be reduced by appropriate design**



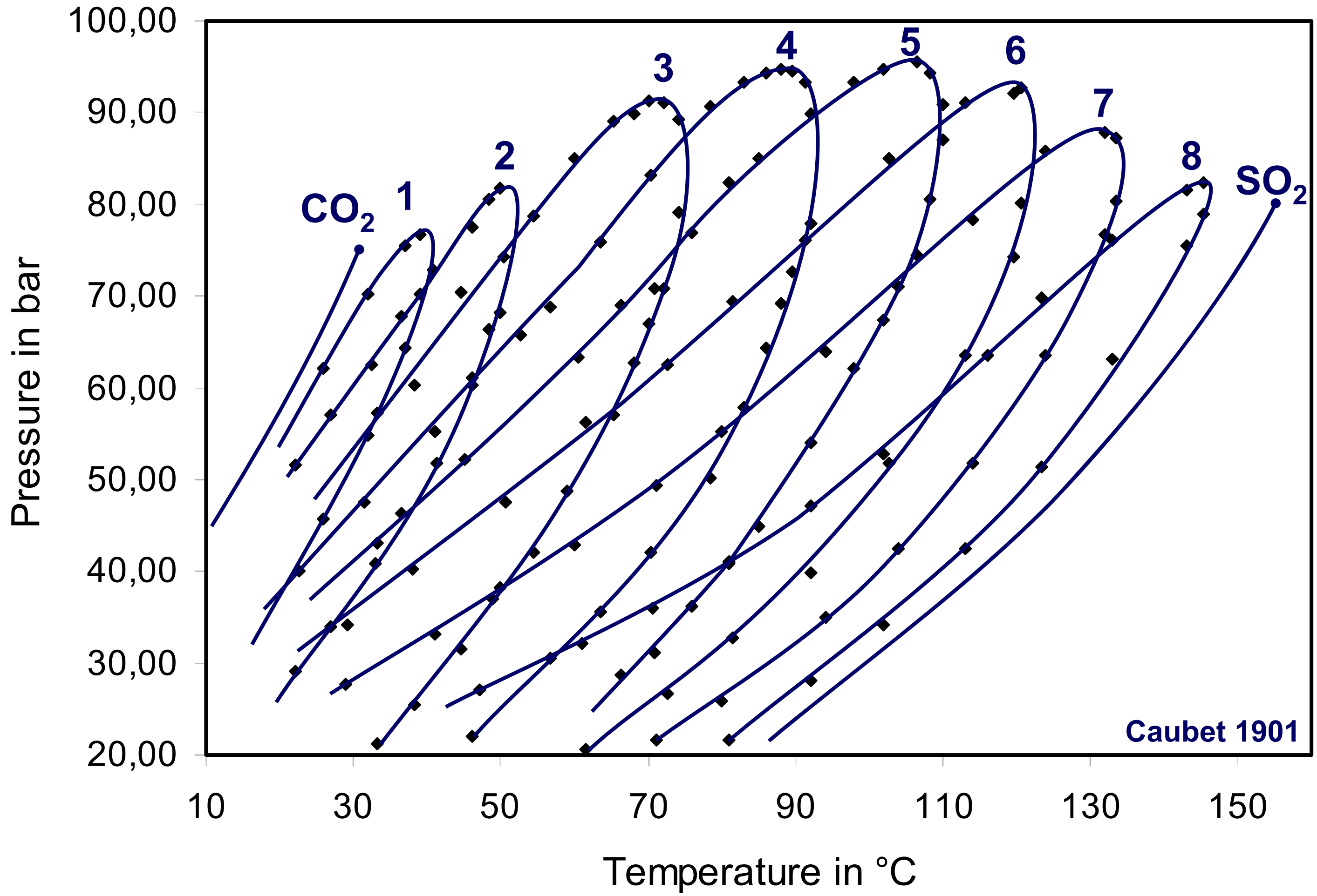
Phase Equilibrium of Argon – CO_2

TUHH
Technische Universität Hamburg-Harburg

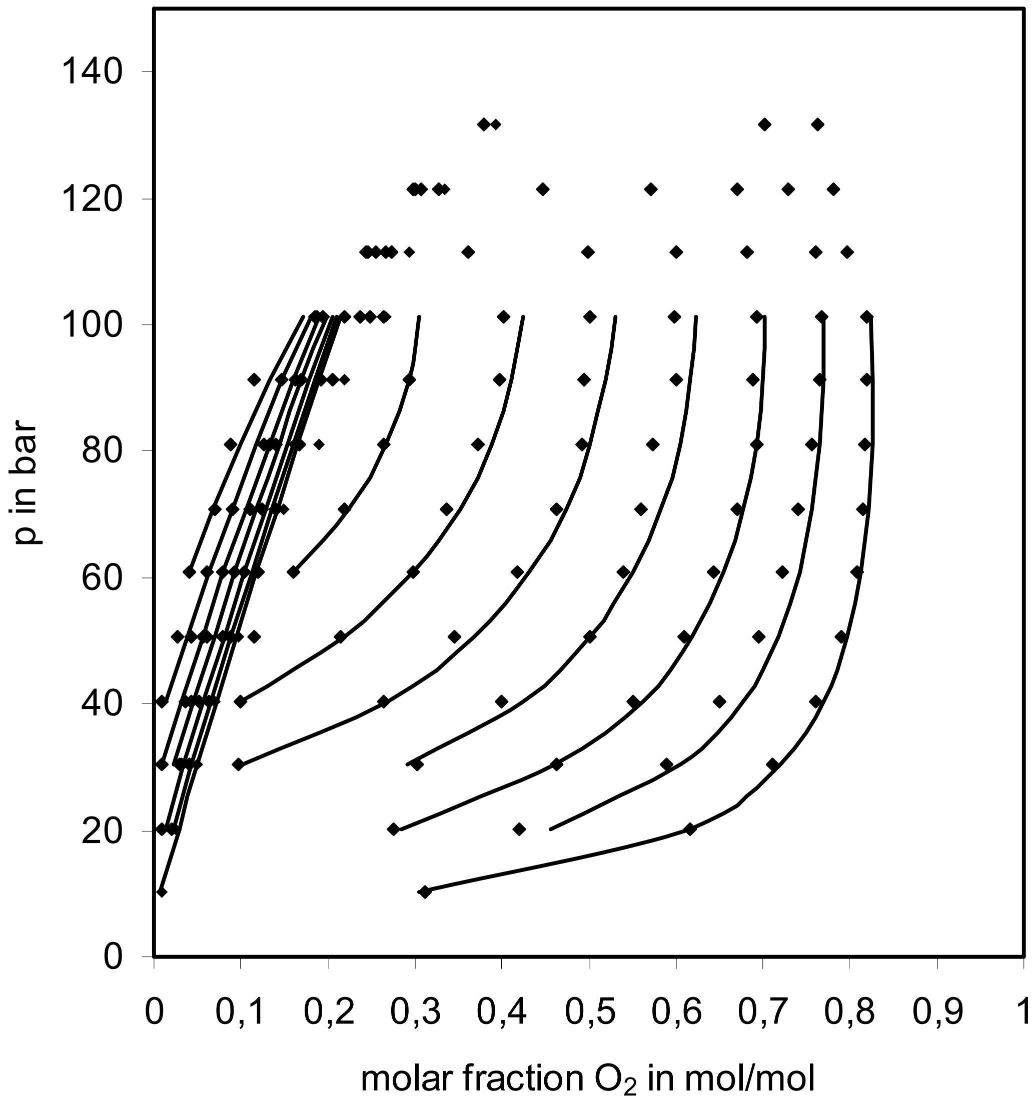


Phase Equilibrium of SO_2 – CO_2

TUHH
Technische Universität Hamburg-Harburg

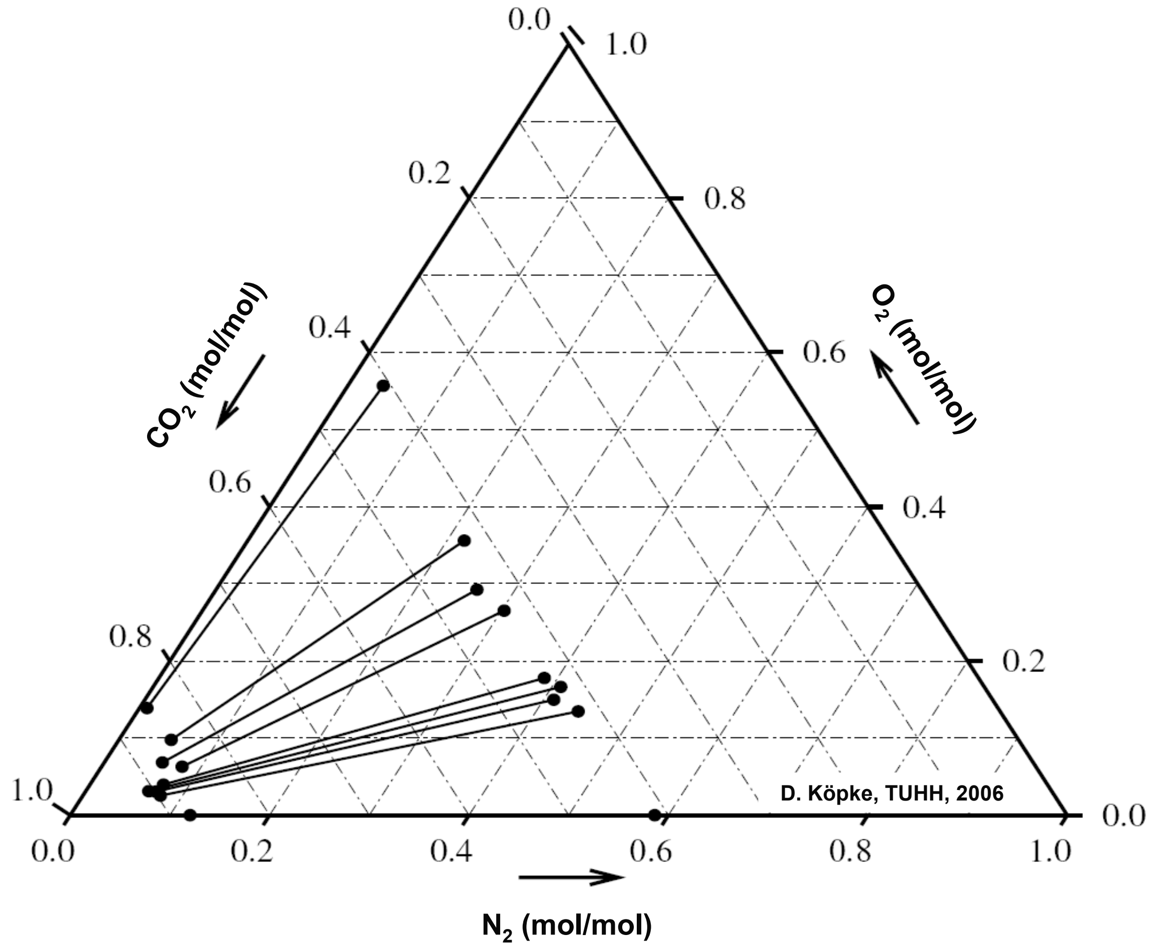


Phase Equilibrium of O_2 – CO_2



Multi-Component Phase Equilibrium $O_2 - N_2 - CO_2$

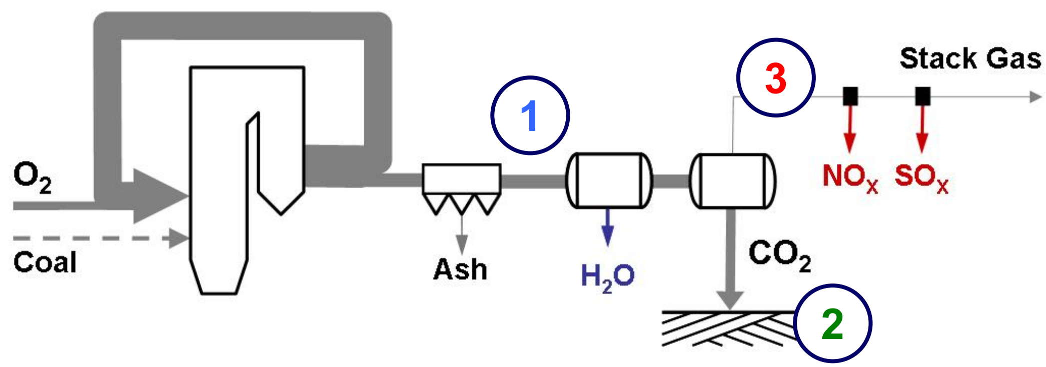
TUHH
Technische Universität Hamburg-Harburg



- **For low purity requirements of the liquefied CO_2**

  ➡ **DeNOx and FGD treat only 3 – 4 % of the total flue gas volume**
  (referred to the total flue gas before the recycle branching)

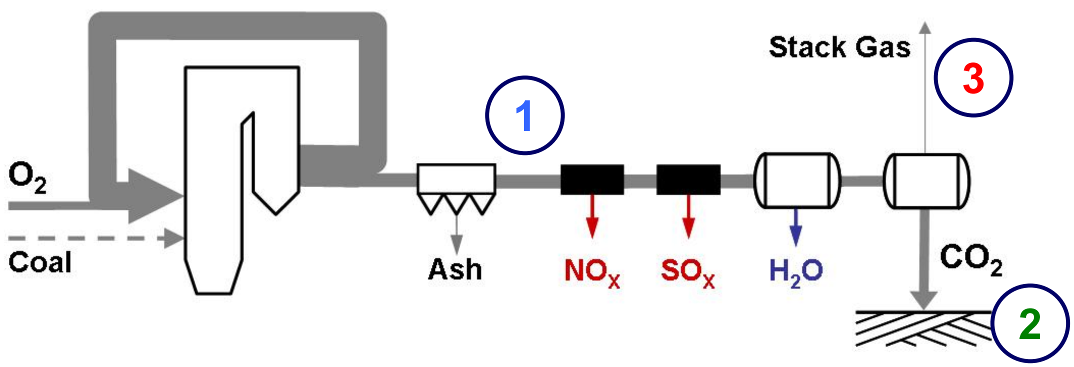
	All values as molar-%	CO_2	N_2	Ar	O_2	SO_2	NO_x
1	Flue Gas, dry	89.1	5.0	0.6	5.0	0.3	482 ppm
2	CO_2	98.8	0.3	450 ppm	0.4	0.4	335 ppm
3	Stack Gas	47.3	25.2	2.9	24.6	34 ppm	<1 ppm



Flue Gas Treatment for **Higher Purity Requirements**

- For **higher purity requirements of the liquefied CO_2**
  - ➡ **DeNOx and FGD prior to CO_2 capture**
  - ➡ **DeNOx and FGD treat now 30 % of the total flue gas volume** (referred to the total flue gas before the recycle branching)

All values as molar-%	CO_2	N_2	Ar	O_2	SO_2	NO_x
1 Flue Gas, dry	89.4	5.0	0.6	5.0	47 ppm	48 ppm
2 CO_2	99.2	0.3	449 ppm	0.4	57 ppm	34 ppm
3 Stack Gas	47.3	25.2	2.8	24.6	<1 ppm	<1 ppm

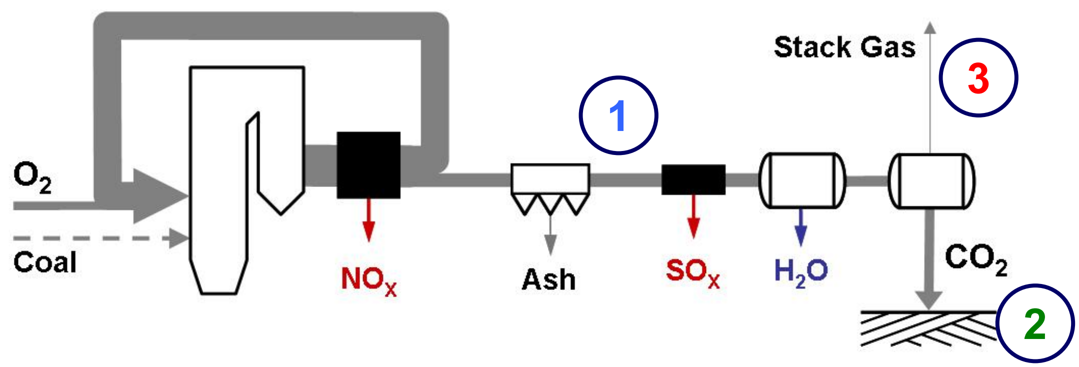


Flue Gas Treatment for **Highest Purity Requirements**

TUHH
Technische Universität Hamburg-Harburg

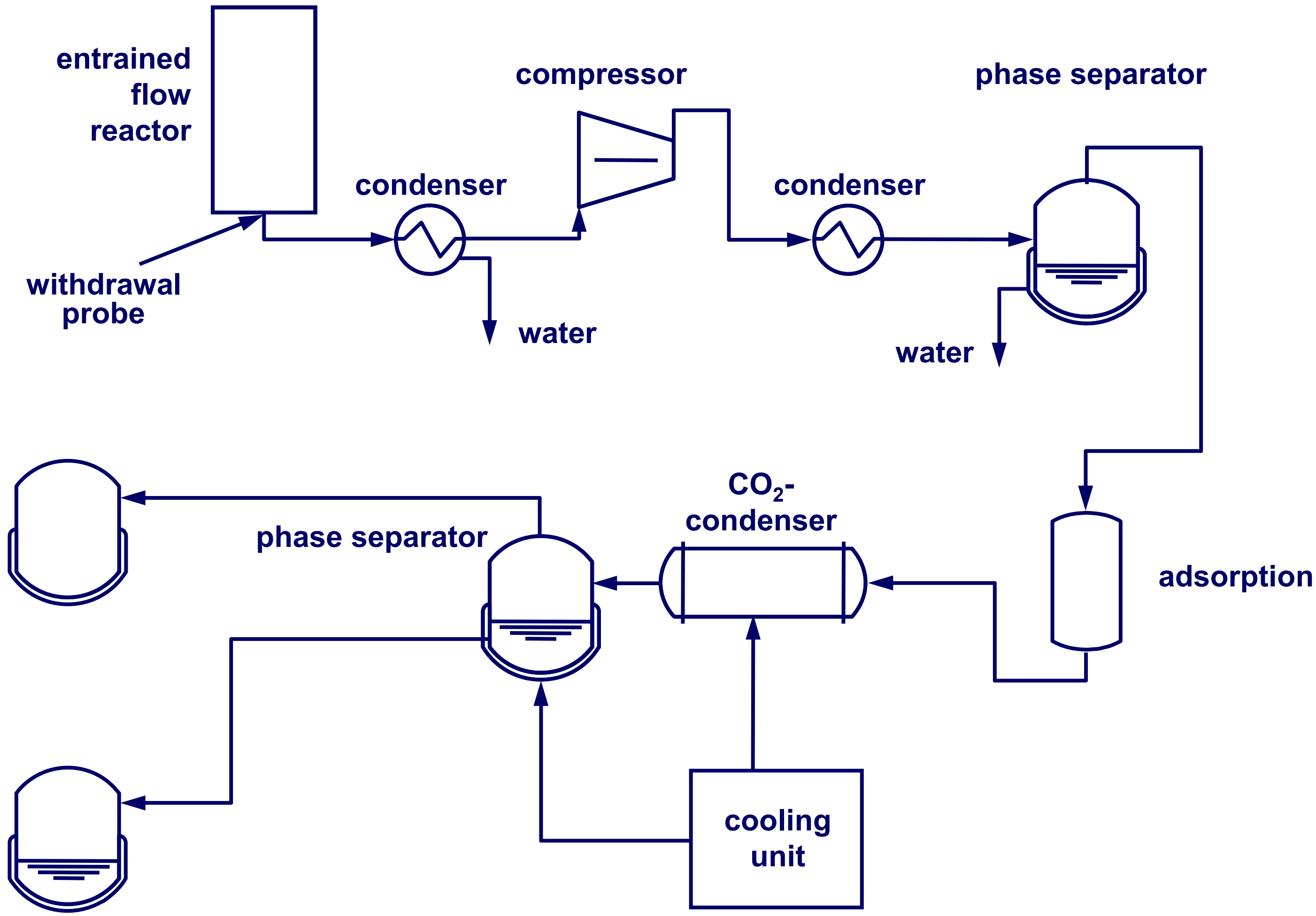
- For **highest purity requirements of the liquefied CO_2**
  - ➡ DeNOx is now needed before recycle branching
  - ➡ Even higher purity requirements would result in unusual processes with still higher power demands

All values as molar-%	CO_2	N_2	Ar	O_2	SO_2	NO_x
1 Flue Gas, dry	89.4	5.0	0.6	5.0	47 ppm	23 ppm
2 CO_2	99.2	0.3	449 ppm	0.4	57 ppm	16 ppm
3 Stack Gas	47.3	25.2	2.8	24.7	<1 ppm	<1 ppm

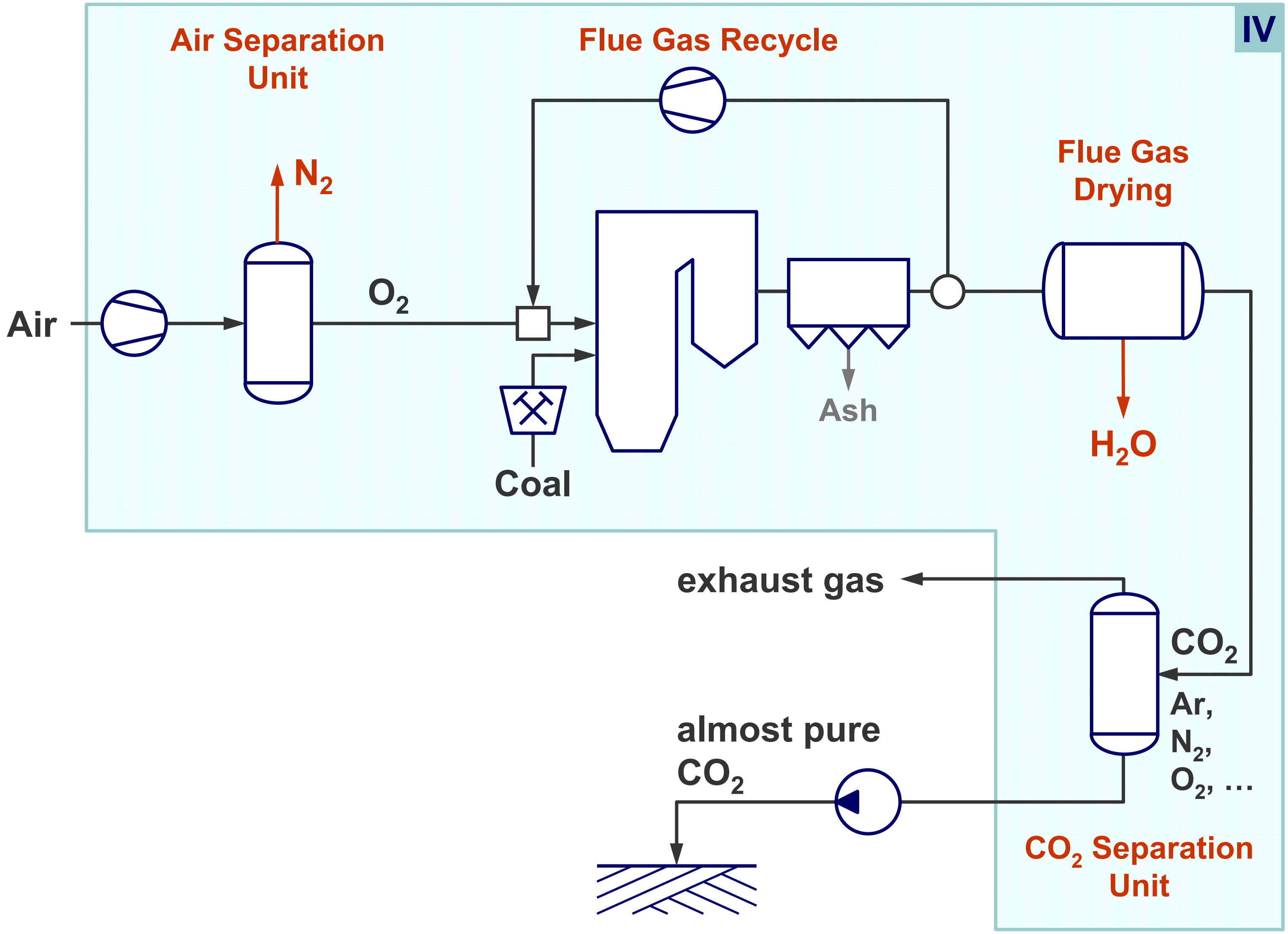


Test CO_2 Separation Plant at the Institute of Energy Systems

TUHH
Technische Universität Hamburg-Harburg



Up to now: Phase Equilibria - This test plant: Kinetic Behavior


IV
Air Separation Unit
Flue Gas Recycle
Flue Gas Drying
N_2
O_2
Air
Coal
Ash
H_2O
exhaust gas
CO_2
Ar,
N_2,
O_2, …
almost pure CO_2
CO_2 Separation Unit

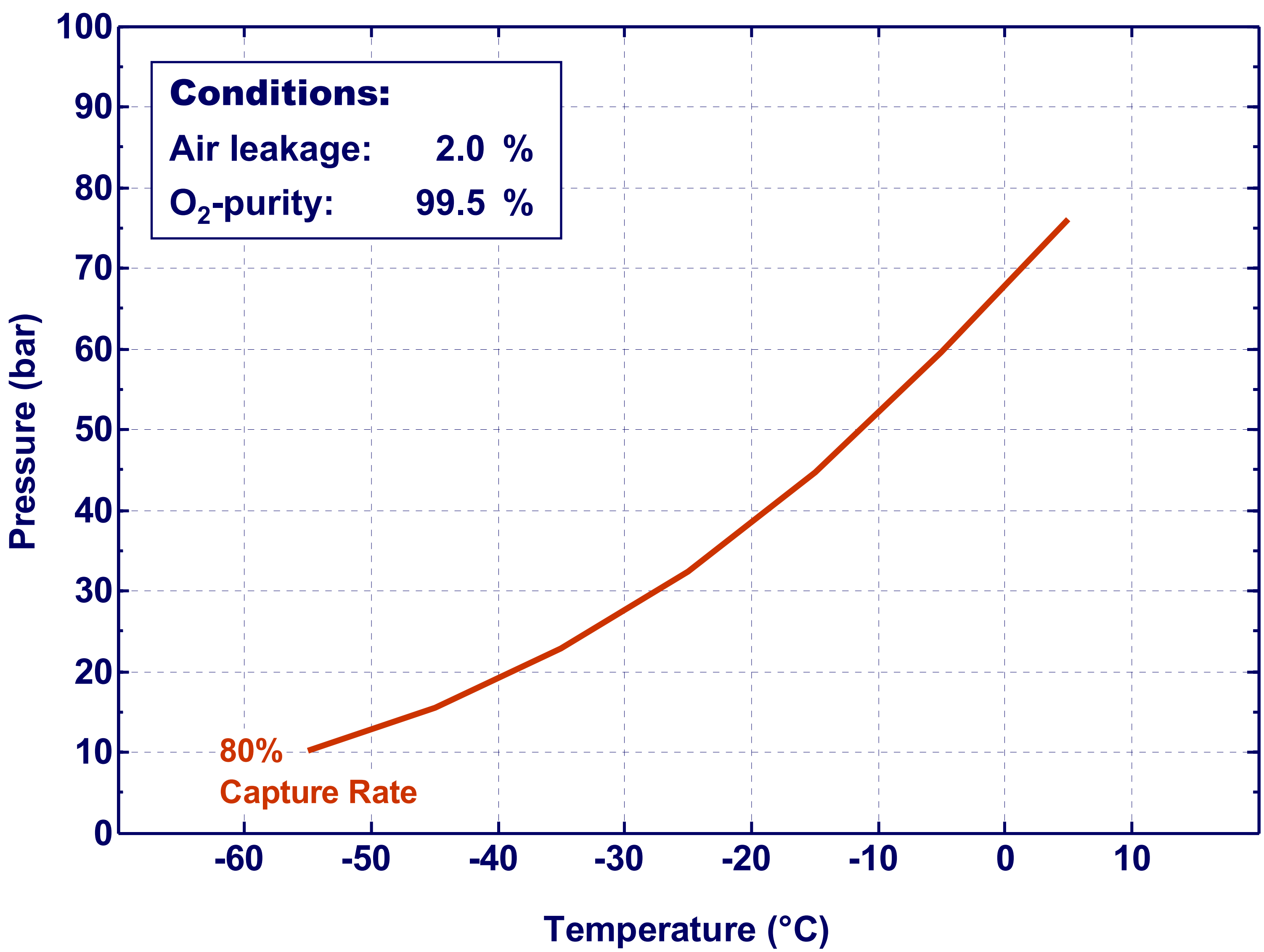
TUHH
Technische Universität Hamburg-Harburg

- **Simulation of the overall process**
  - **Definition of the global parameters supported by subprojects and industry**
  - **Commercial software: Ebsilon®, Aspen®**
  - **Continuous integration of the results of the subprojects**
  - **Use of state of the art technology**

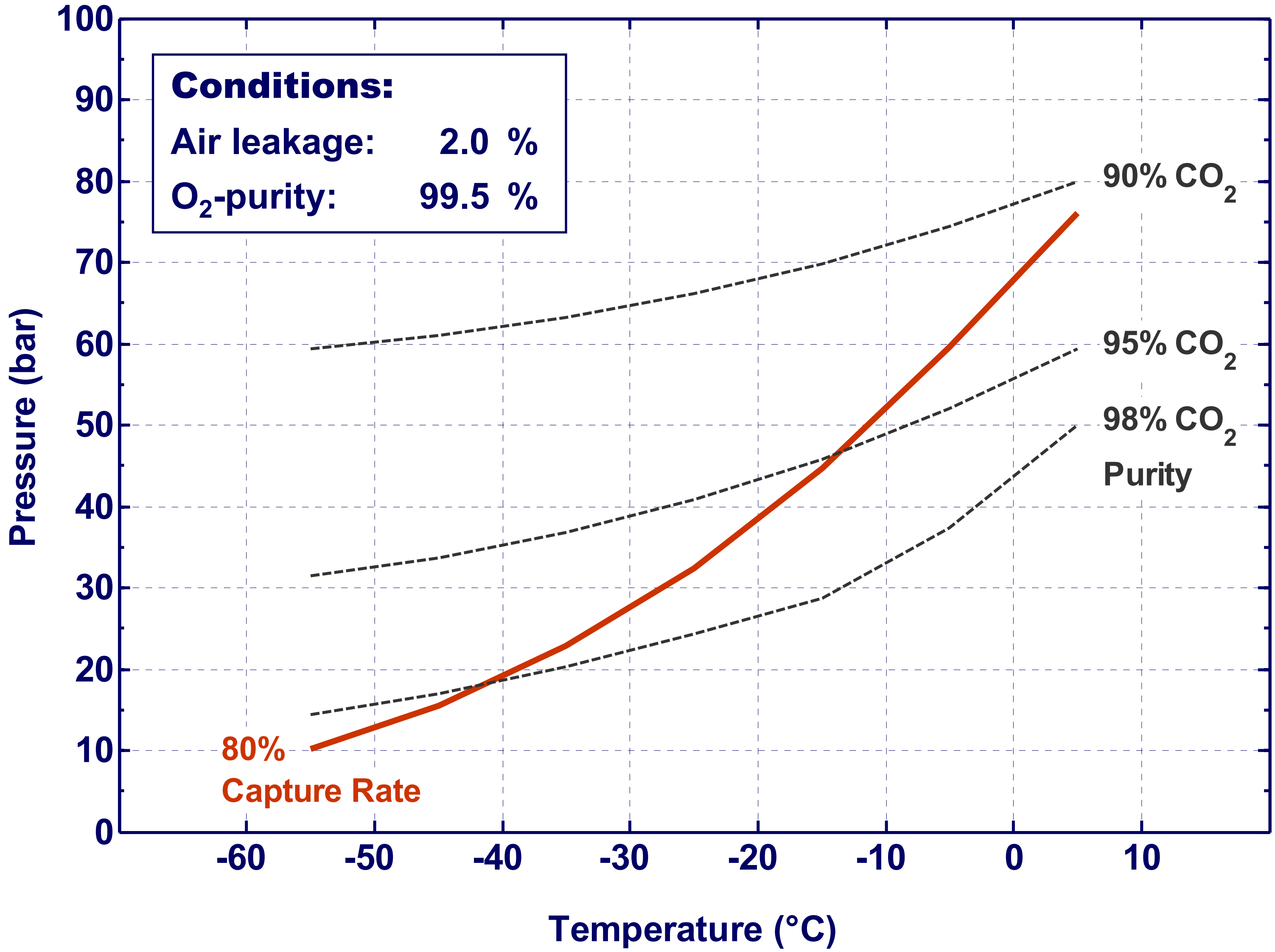
- **Objectives**
  - **Feasibility**
  - **Process optimization (overall energetic efficiency)**
  - **Clarification of important details** (e.g. CO_2 purity, part-load behavior)
  - **Economic efficiency**

p-T-diagram for Single-Stage Cryogenic CO_2 Liquefaction

TUHH
Technische Universität Hamburg-Harburg

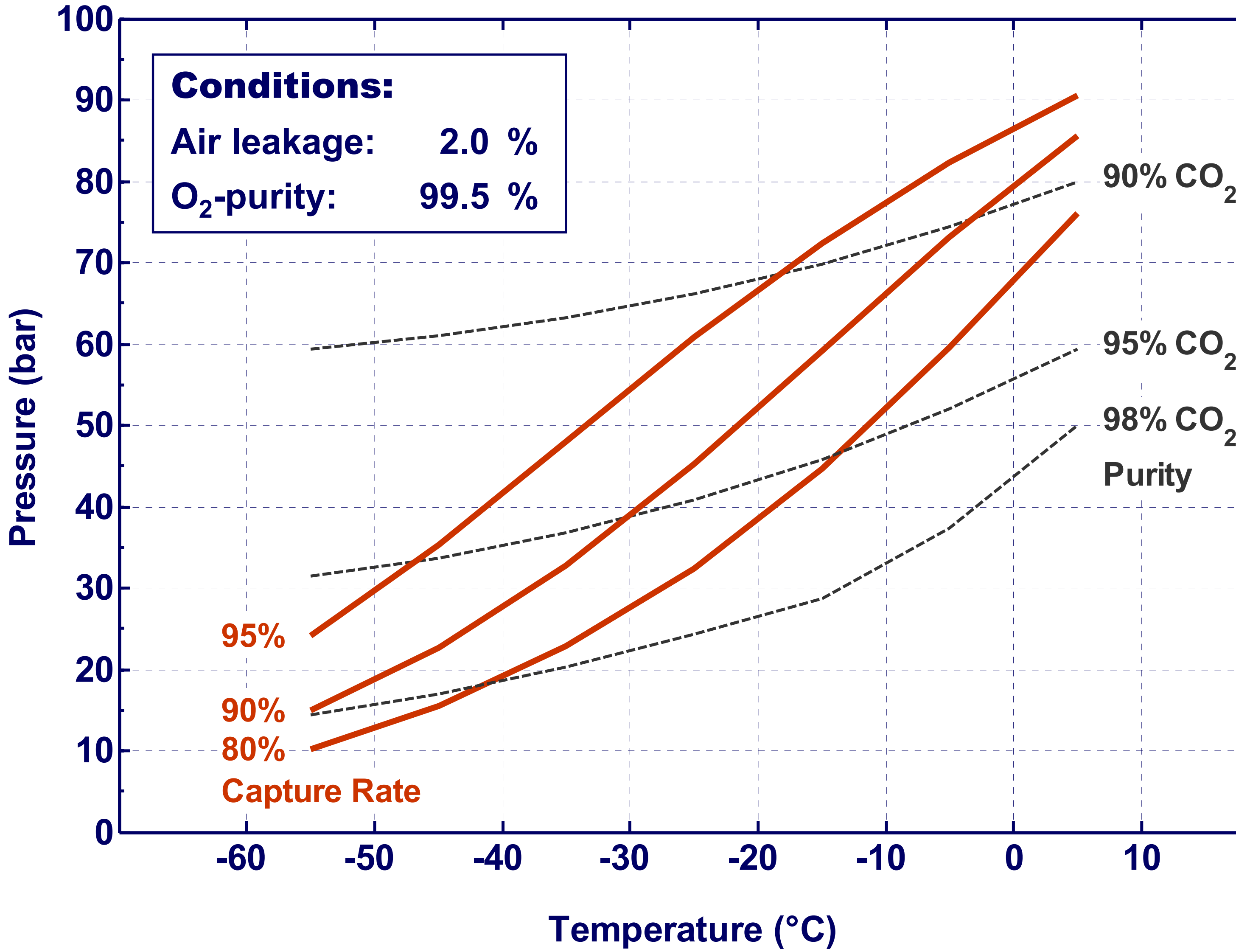


p-T-diagram for Single-Stage Cryogenic CO_2 Liquefaction



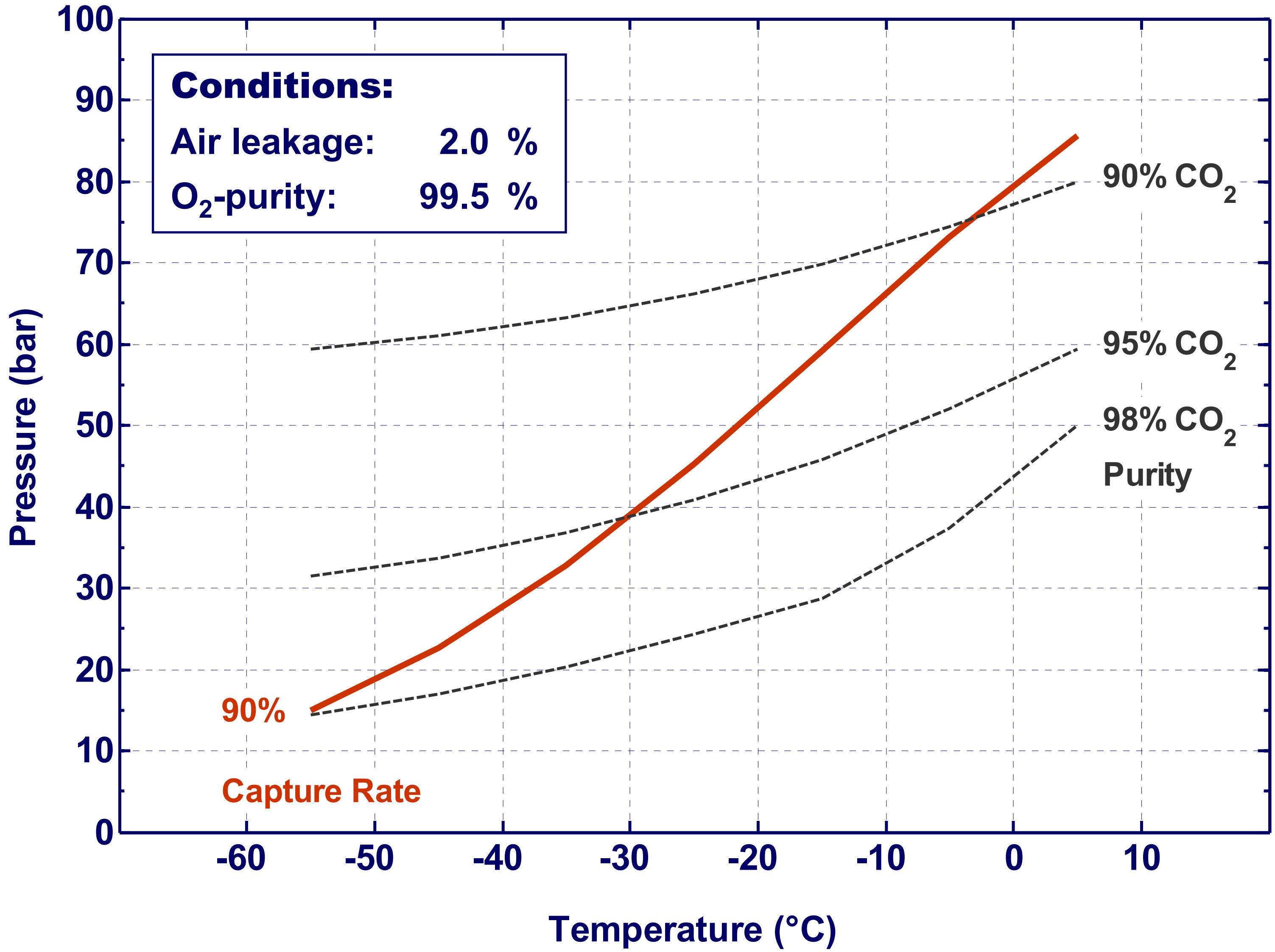
p-T-diagram for Single-Stage Cryogenic CO_2 Liquefaction

TUHH
Technische Universität Hamburg-Harburg



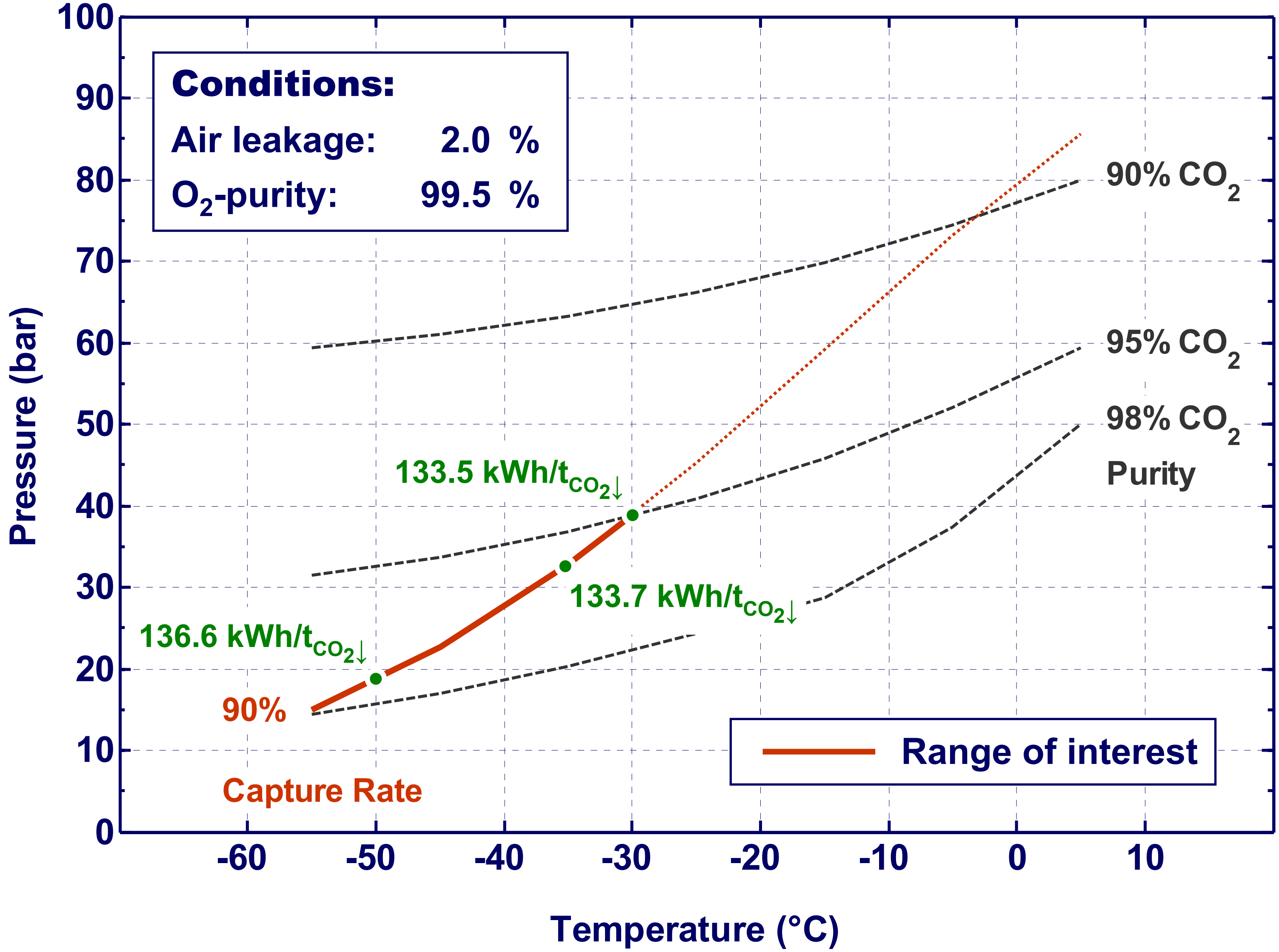
p-T-diagram for Single-Stage Cryogenic CO_2 Liquefaction

TUHH
Technische Universität Hamburg-Harburg



p-T-diagram for Single-Stage Cryogenic CO_2 Liquefaction

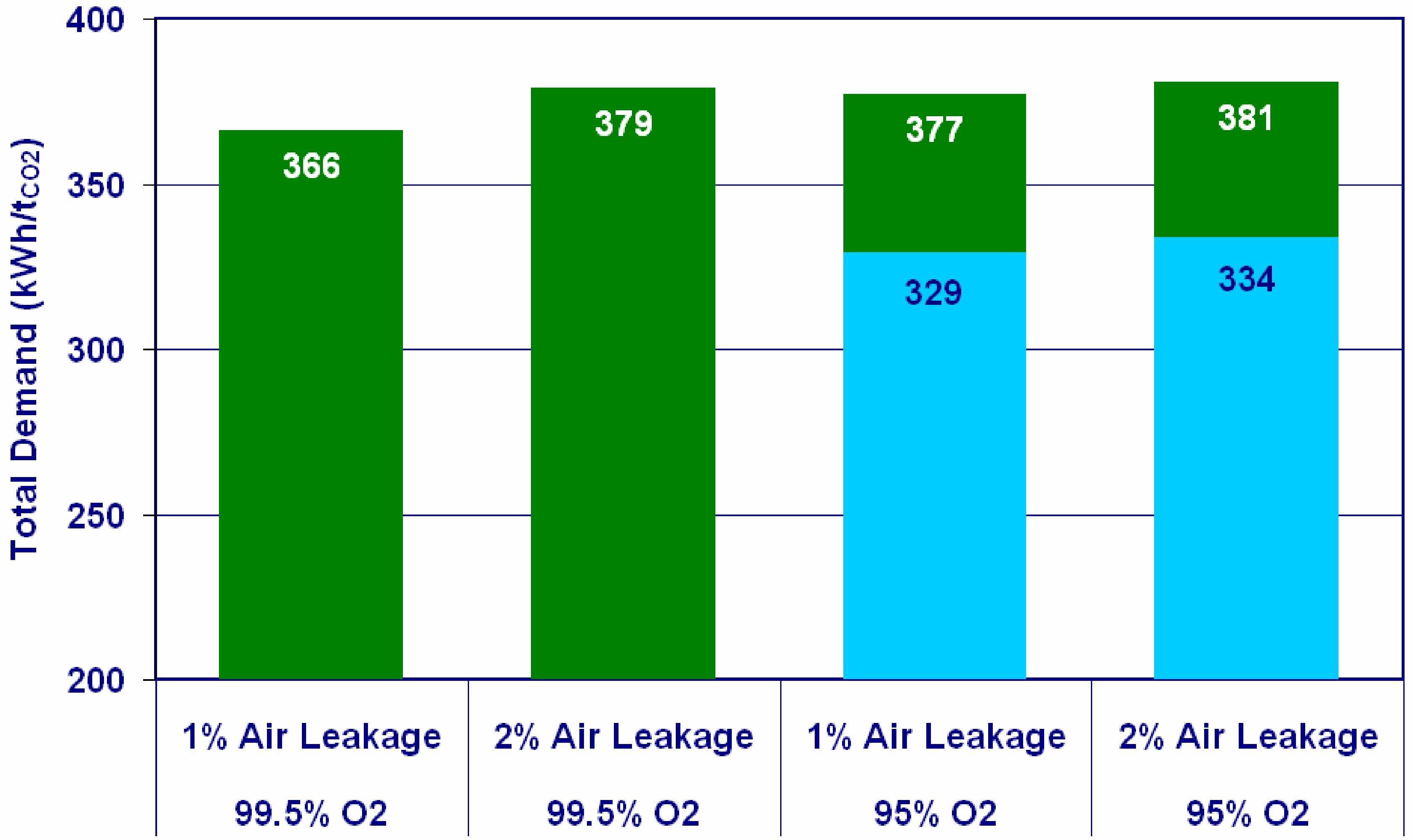
TUHH Technische Universität Hamburg-Harburg



Overall Energy Demand

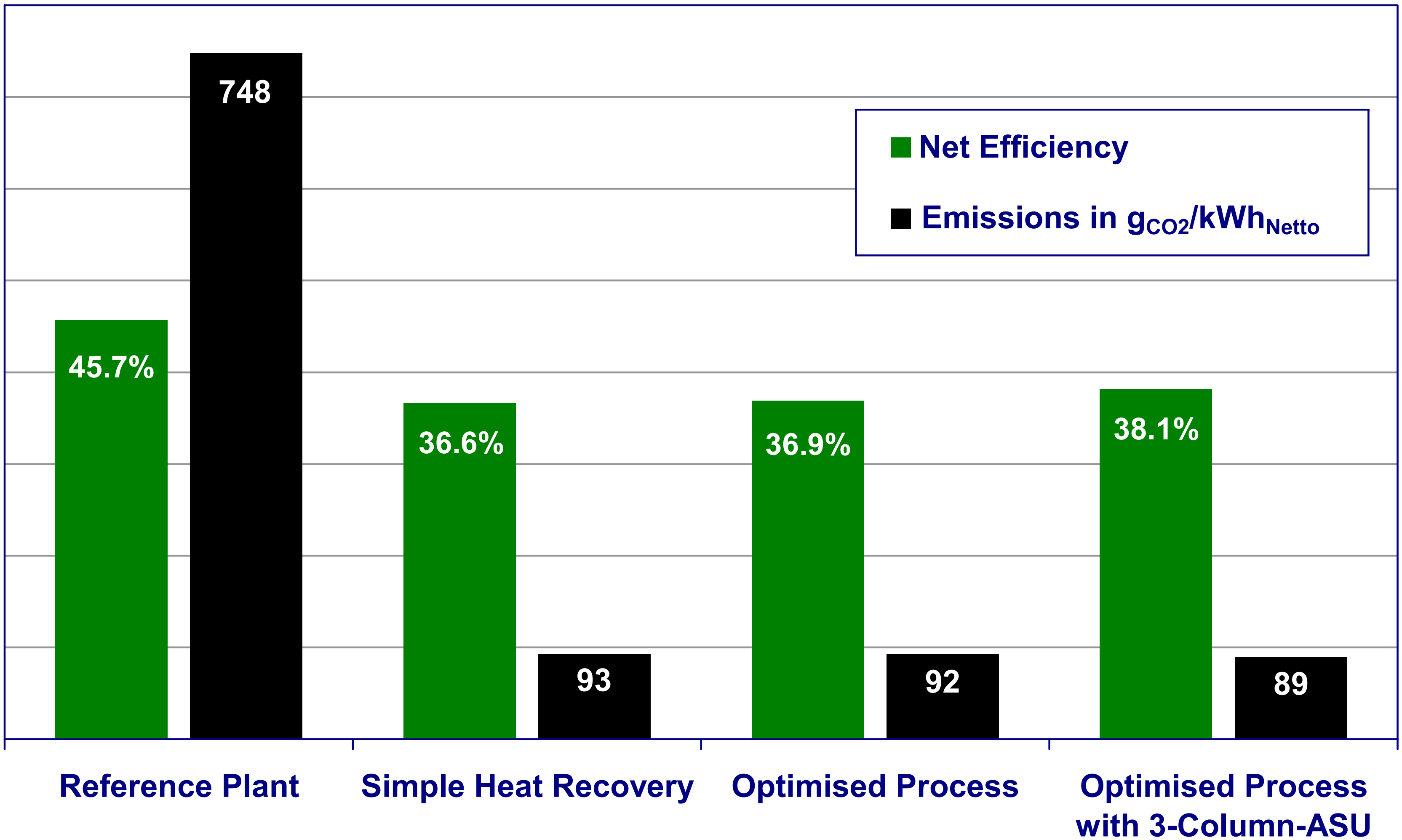
TUHH
Technische Universität Hamburg-Harburg

Requirements: 90 % capture rate and CO_2-purity > 95%



Comparison of Different Processes
(1% Leakage, Capture Rate 90%, Purity > 98,5%)

TUHH
Technische Universität Hamburg-Harburg



Thank you for your attention!

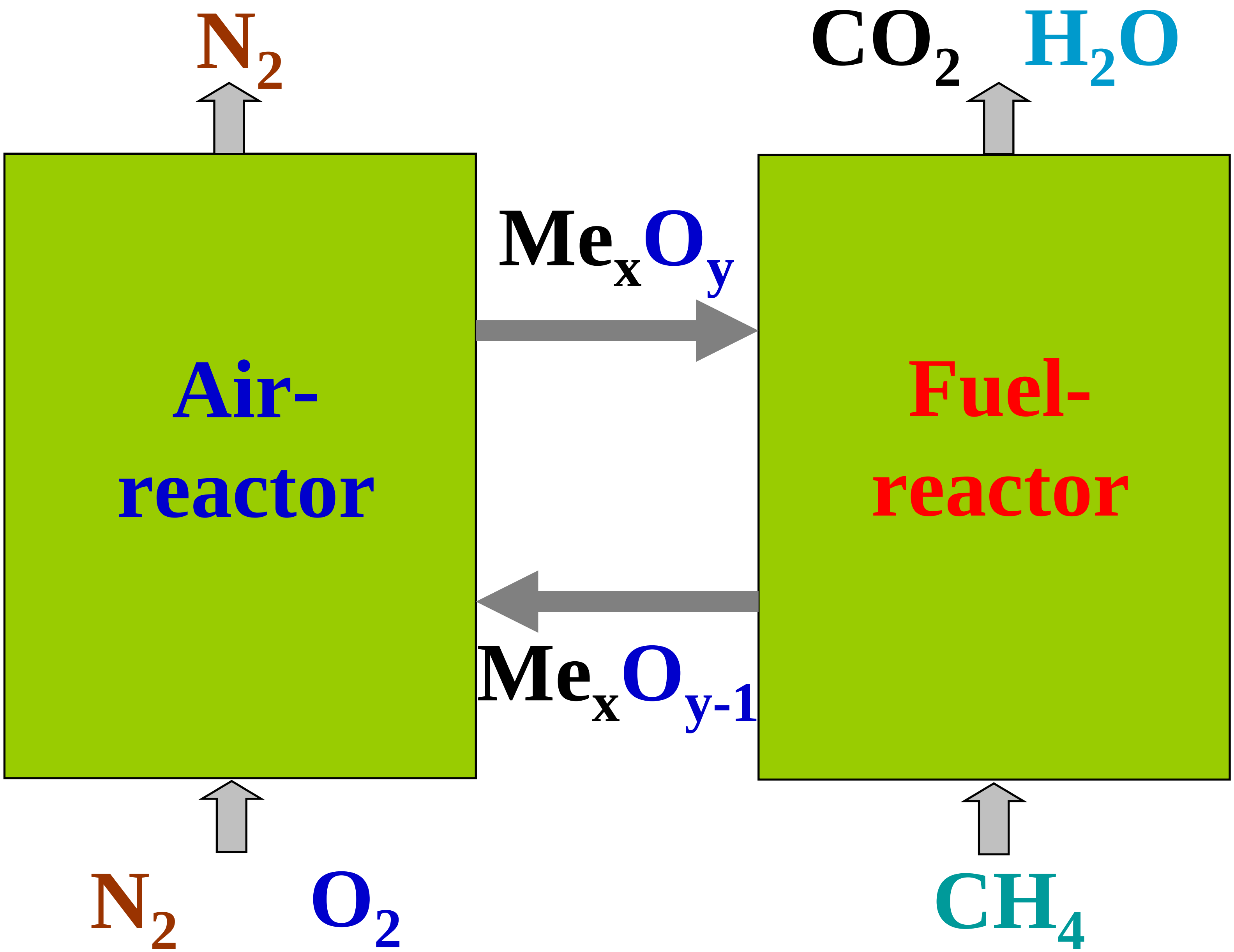
CHEMICAL-LOOPING COMBUSTION USING GASEOUS AND SOLID FUELS

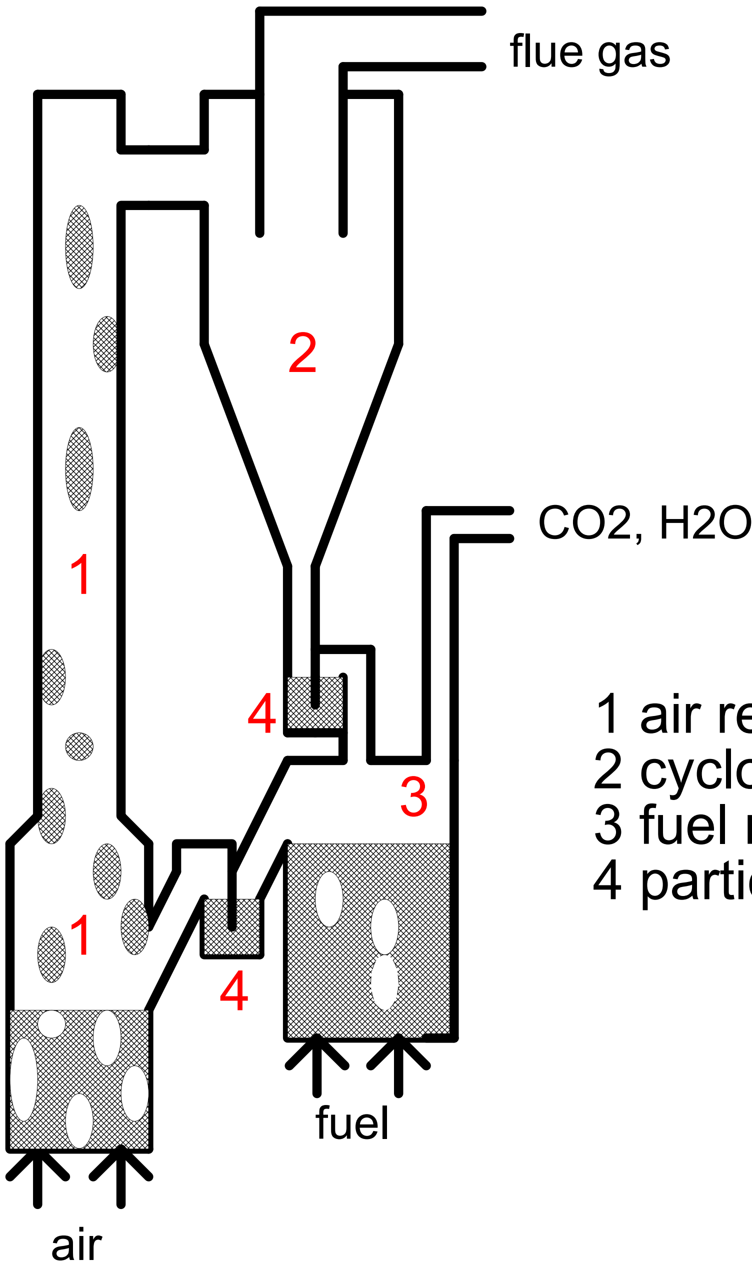
Tobias Mattisson,
Chalmers University of Technology
Göteborg, Sweden

Chemical-looping combustion

- A process for oxidizing fuels using metal oxides as oxygen carriers, transferring oxygen from combustion air to fuel.

- No mixing of combustion air and fuel => CO_2 can be obtained pure, without (!) separation of gases


N2
CO2 H2O
MexOy
Air-
reactor
Fuel-
reactor
MexOy-1
N2 O2
CH4



1 air reactor, riser
2 cyclone
3 fuel reactor
4 particle locks

Chemical-looping combustion, status 2002:

- ”paper concept”,
- process never tested
- a limited number of particles tested in a limited number of cycles

What has happened since then ?

>300 particles have been tested:

- active oxides primarily NiO, CuO, Mn_3O_4, Fe_2O_3
- support materials, e.g. Al_2O_3, TiO_2, SiO_2, ZrO, sepiolite, $MgAl_2O_4$ ...
- various mixing ratios active oxide/support
- production methods: extrusion, freeze-granulation, wet methods, impregnation ...
- heat treatment: typically 900-1300 C
- tests performed in batch fluidized bed reactors, TGA, continuous CLC reactors

Pros and cons for the active oxides

	Fe	Mn	Cu	Ni
Reactivity	- -	-	+	++
Cost	++	+	-	- -
Health				-
Thermodynamics				-[1]
Reaction with CH_4			+[2]	
Melting point			-[3]	

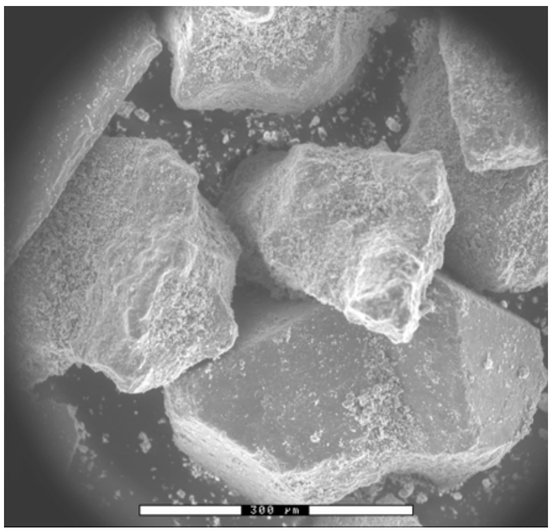
[1]maximum conversion 99-99.5%

[2]exothermic reaction in fuel reactor

[3]melting point Cu: 1085 C

Three different types of oxygen carriers based on Fe_2O_3

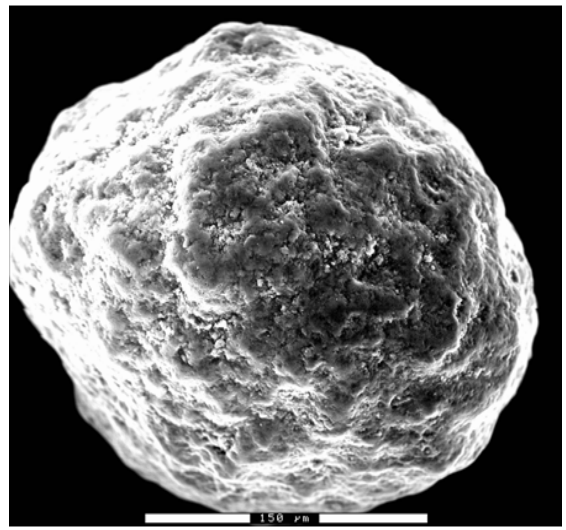
Iron ore



BET=3,7 m^2/g

Pore volume=0,012 cm^3/g

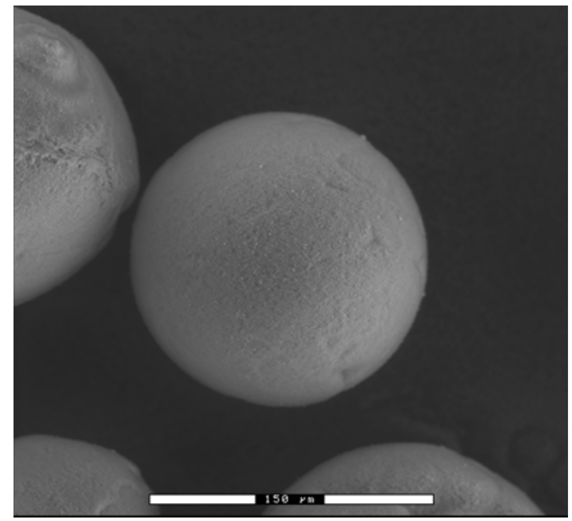
Impregnated



BET=80,8 m^2/g

Pore volume=0,35 cm^3/g

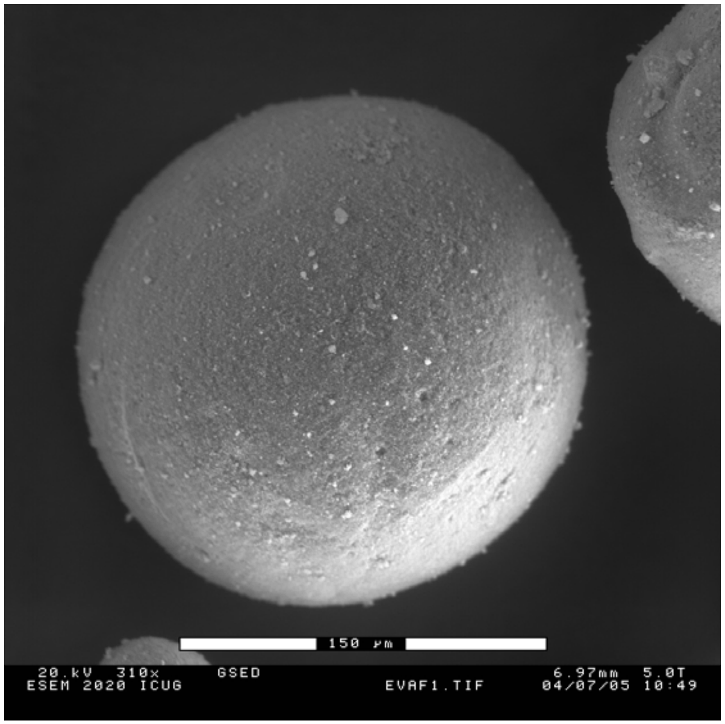
Freeze granulated

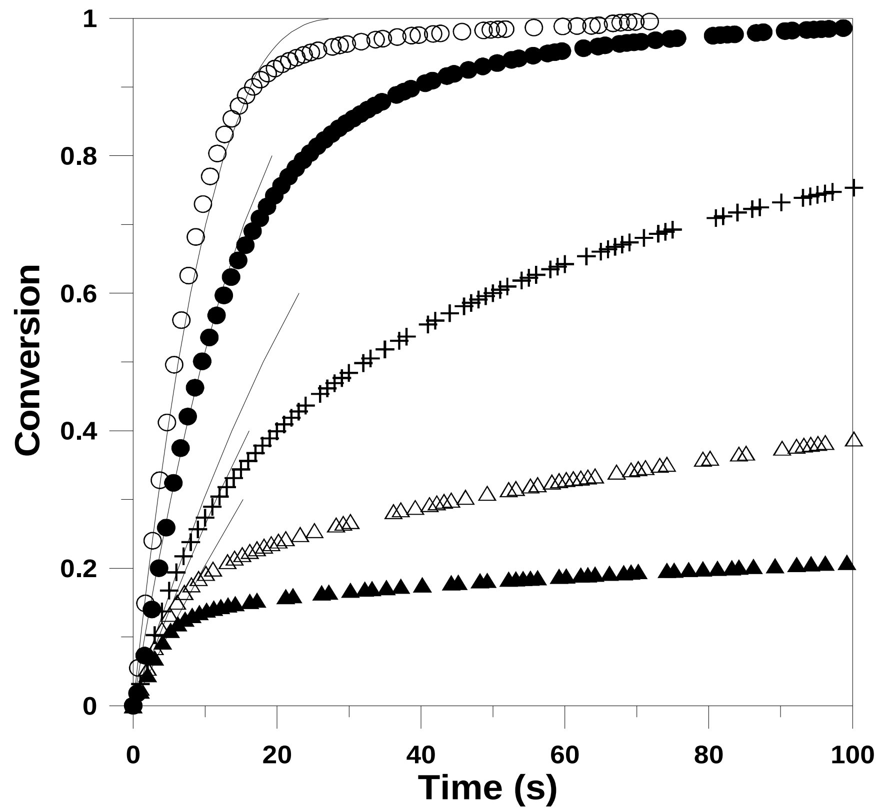


BET=8,3 m^2/g (high)

Pore volume=0,33 cm^3/g

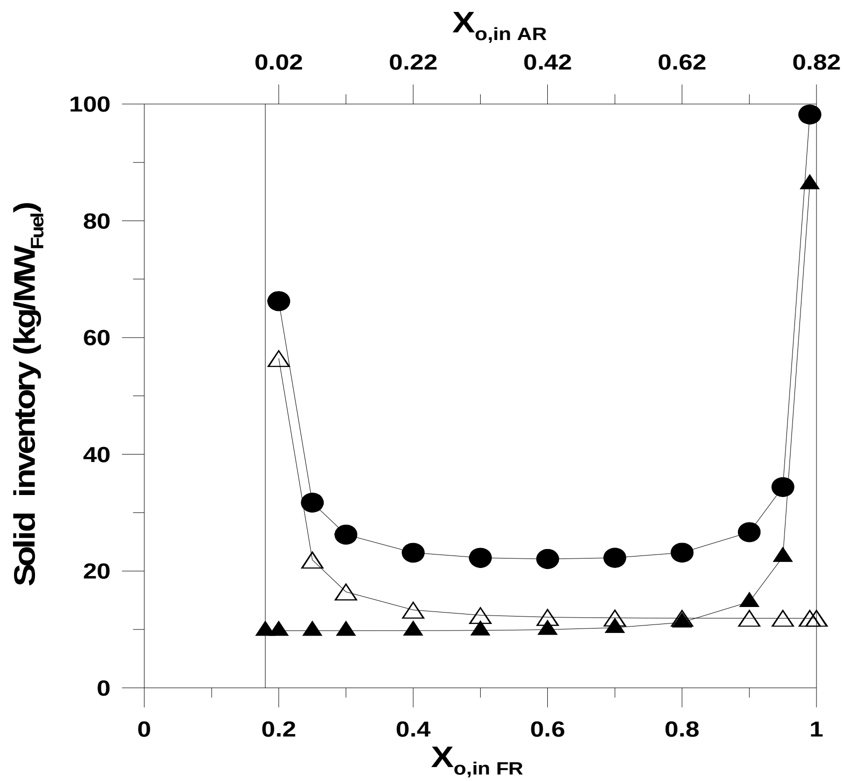
Results from reactivity investigation (TGA) of an oxygen carrier of $NiO/MgAl_2O_4$ produced by freeze granulation





Effect of temperature on the reduction reaction using CH_4 (10%) at 800°C (▲), 850°C (Δ), 900°C (+), 950°C (●) and 1000°C (○).Continuous line: results predicted by shrinking-core model for spherical grains.

How much material of this carrier is needed in the fuel and air reactor?



Solid inventory as a function of solid conversion at the inlet of fuel reactor (Xo,inFR) and air reactor (Xo,inAR) mFR (Δ),mAR (▲) and mtotal (●).

Small 300 W chemical-looping combustor

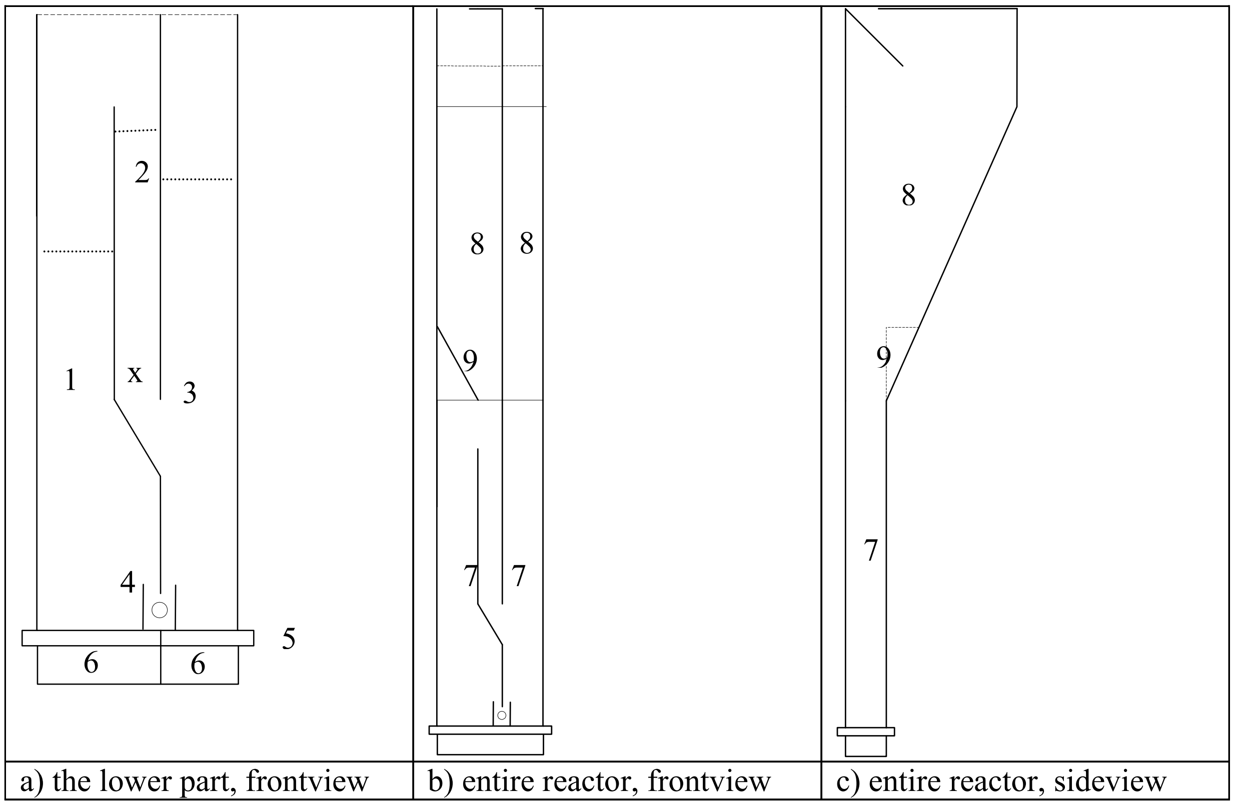
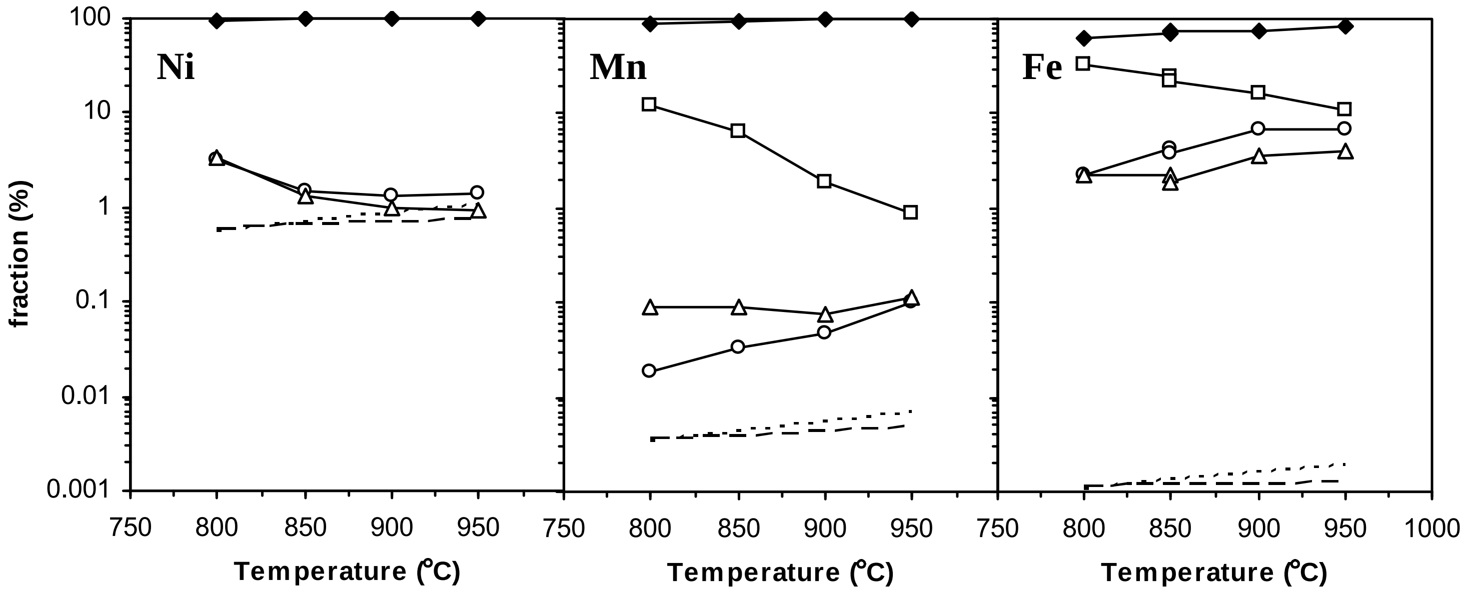


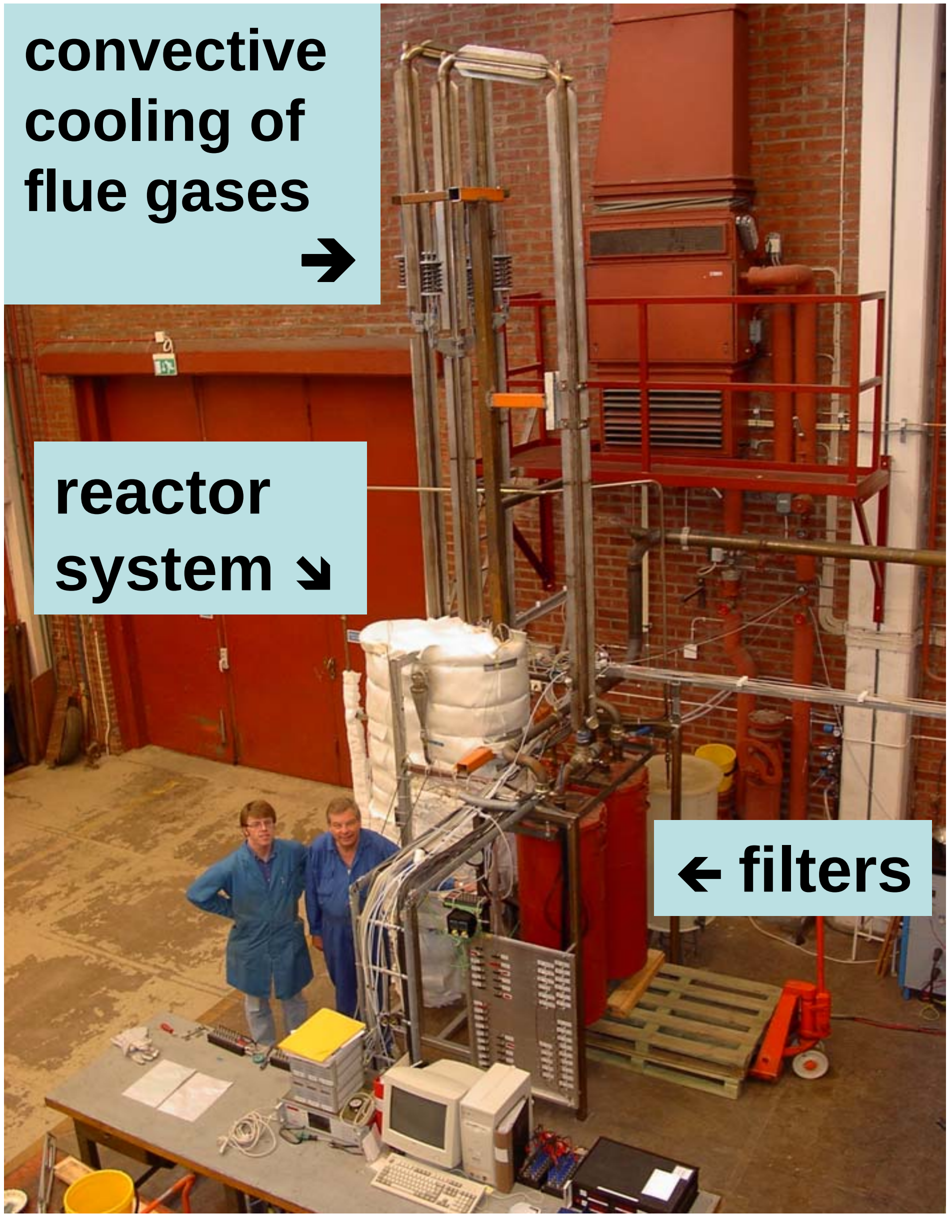
Figure 2. The principal sketch of the reactor. 1) air reactor, 2) downcomer, 3) fuel reactor, 4) slot, 5) gas distributor plate, 6) wind box, 7) reactor part, 8) particle separator, 9) leaning wall. Fluidization in the downcomer (x) and slot (o) is also indicated. The dashed lines indicates the bed heights during combustion.

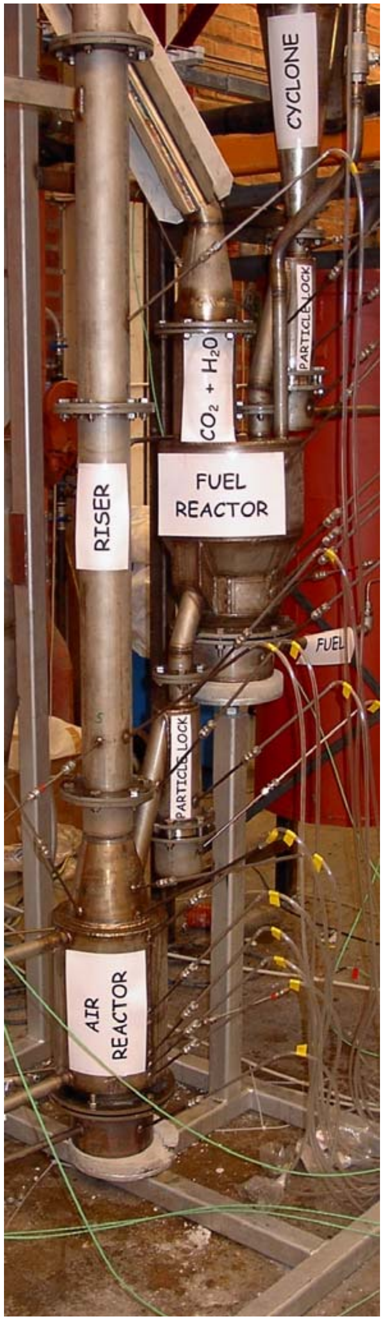
Chalmers' 300 W chemical-looping combustor 2004

Results from tests in 300 W continuous reactor with three types of particles using natural gas



Chalmers' 10 kW chemical-looping combustor 2003





Conclusions (Ni-based particles):

No CO_2 from air reactor:

- **No leakage between reactors**
- **No significant carbon formation**
- **➔ 100% CO_2 capture**

Sand tests show no leakage from air to fuel reactor:

- **Almost pure CO_2 possible**
  1.2% H_2, 0.6% CO with NiO

Conversion of fuel:

- **99.5% at 800**

Operation

- **Stable and easy to control**
- **105 h operation CLC (13 days) without change of particles**
- **~300 h circulation**

Investigation of particles after 105 h

- **No loss in reactivity**
- **No loss in particle strength**

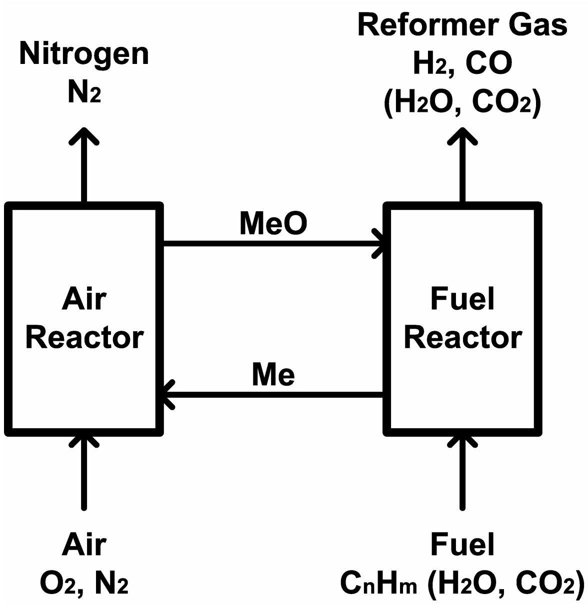
Loss of fines very low:

- **Particle lifetime >40,000 h (?)**

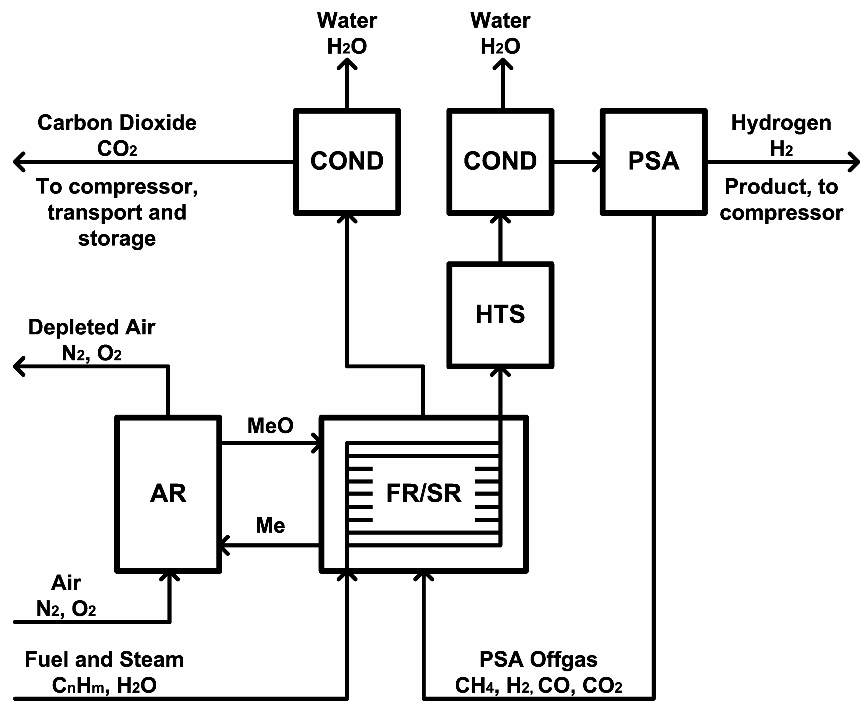
Low particle cost:

- **<1 €/ton CO_2 (lifetime 4,000 h)**

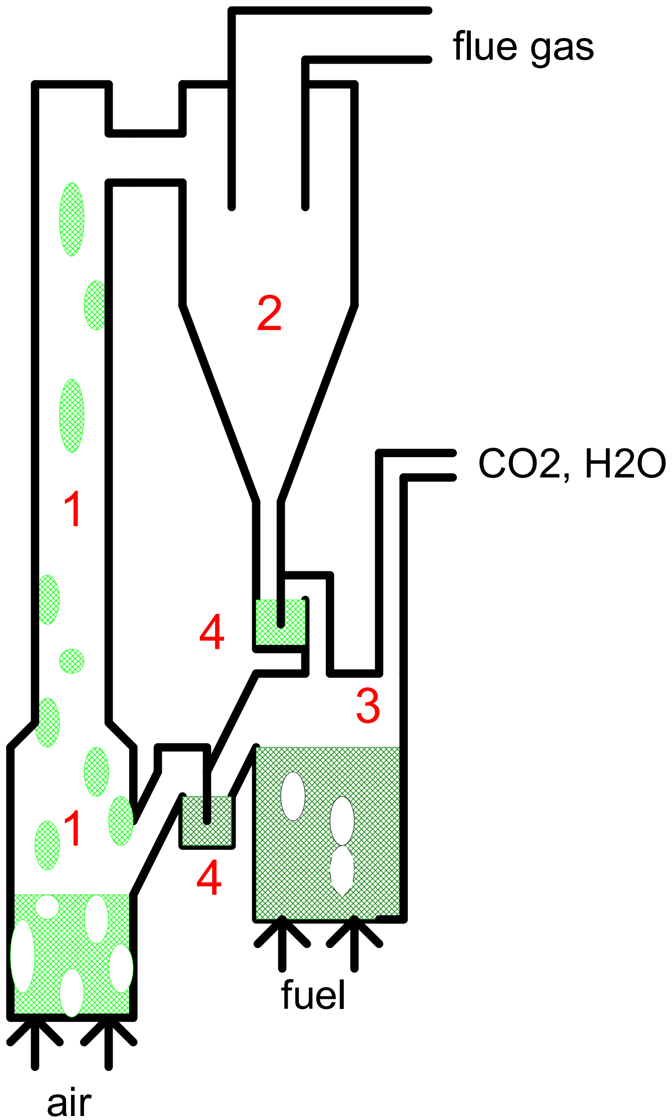
Hydrogen production using chemical-looping technology



Chemical looping reforming by partial oxidation



Hydrogen production by steam reforming with chemical-looping as heat source and separation off-gas as fuel.



1 air reactor, riser
2 cyclone
3 fuel reactor
4 particle locks

Solid fuels application

- **Solid fuels reacts indirectly with ox.carrier, via gasification step**
- **Char may follow particles to air reactor => incomplete capture**
- **Gasification slow => large residence time => large solids inventory in fuel reactor**
- **Less effective contact between fuel gas and oxygen carrier**
- **Ash may reduce oxygen carrier life-time**

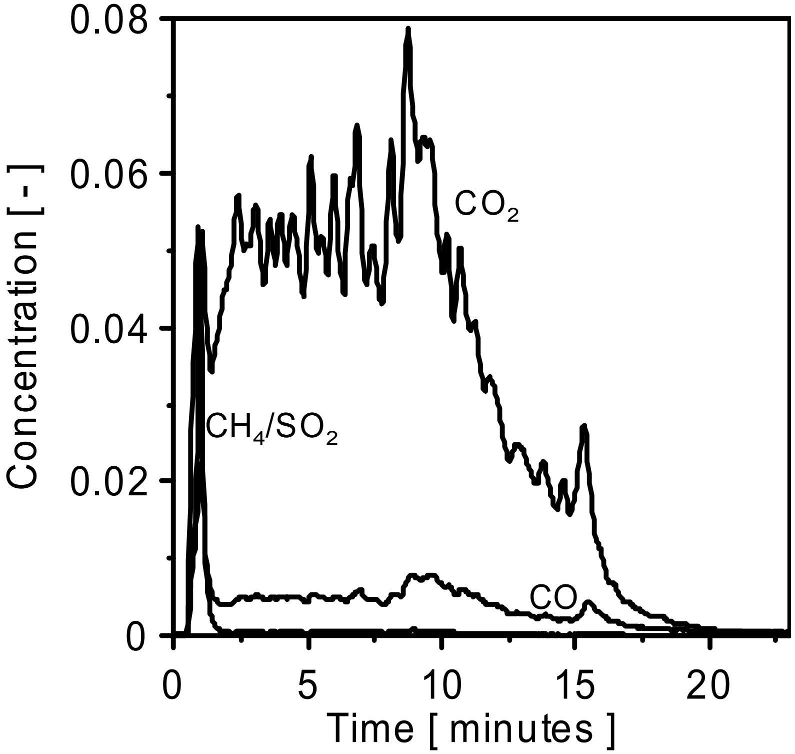
Fundamental principles

Gasification

Char is gasified in environment of highly reducing gas, in order to achieve gas with high heating value.
=> low concentration of reacting gas (H_2O, CO_2), high concentration of inhibitor (H_2, CO)

Chemical-looping combustion

Char is gasified in environment of oxidizing gas ($H_2O + CO_2$), with rapid removal of gasification products (CO, H_2) already inside the particle phase
=> high concentration of reacting gas (H_2O, CO_2), low concentration of inhibitor (H_2, CO)
=> *much higher rate of conversion*
=> may *avoid negative effects of reducing conditions on ash*

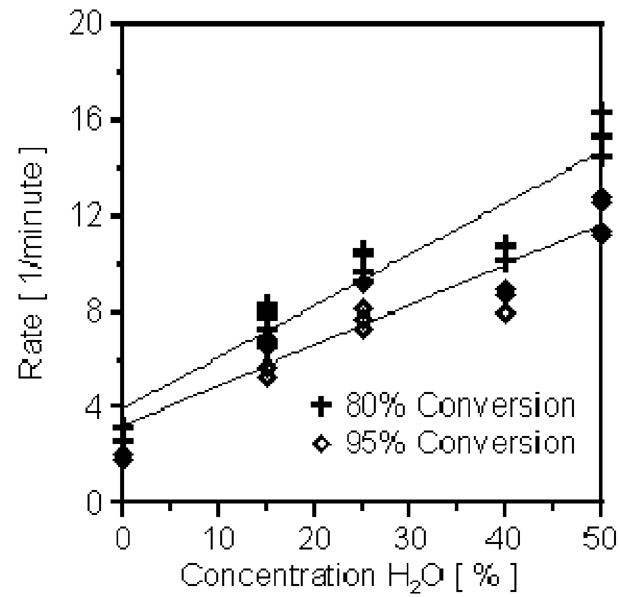


Concentration profile during the reduction of Fe2O3/MgAl2O4 with petroleum coke. The inlet H2O content is 50% and SO_2 0%. The temperature is 950˚C.

- **Laboratory tests of solid fuel (pet. coke) and metal oxide particles verify concept. Air / solid fuel were added in cycles.**

- **Same metal oxide particles were used in 100 h of testing with varying temperature, steam conc., SO_2 conc., defluidization.**

Effect of steam concentration on rate of reaction between petroleum coke and an oxygen carrier of $Fe_2O_3/MgAl_2O_4$



Taken from Leion et al., 2006 (in press)

Chalmers' 10 kW chemical-looping combustor for ***solid fuels,*** 2005

Testing in chemical-looping combustors:

	unit	particle	operation h (hot time[d])	fuel[f]
1	[a]Chalmers 10 kW	$NiO/NiAl_2O_4$	105 (300)	n.gas
2a	[a]Chalmers 10 kW	Fe_2O_3-based	17	n.gas
2b	Chalmers 10 kW	Fe_2O_3-based	16	n.gas.
3	[a]S Korea 50 kW	$Co_3O_4/CoAl_2O_4$	25	n.gas
4	[a]S Korea 50 kW	NiO/bentonite	3[i]	n.gas.
5	[b]Chalmers 300 W	$NiO/NiAl_2O_4$	8 (18)[g]	n.gas
6	[b]Chalmers 300 W	$NiO/MgAl_2O_4$	30 (150)	n.gas/syngas
7	[b]Chalmers 300 W	$Mn_3O_4/ ZrO_{2,\ Mg\text{-}st.}$	70 (130)	n.gas/syngas
8	[c]Chalmers 300 W	Fe_2O_3/Al_2O_3	40 (60)	n.gas/syngas
9	[b]CSIC, 10 kW	$CuO_{impregnated}$	2x100	n.gas
10	[b]Chalmers 300 W	$NiO/MgAl_2O_4$	41 (CLR [g])	n.gas(CLR [g])
11	Chalmers SF[j]	confidential	18	bit. coal

[a]published 2004, [b]published/accepted 2005-2006, [c]submitted [d]total time fluidized at high temperature, [e]same particle as used 100 h in 10 kW unit, [f]n.g. = natural gas, s.g. = syntesgas, [g]chemical-looping reforming, [i]particles fragmentated, [j]10 kW solid fuel CLC,

Chemical-Looping Combustion

Reactor system (fluidized beds):
- well established
- commercially available
- simple
- moderate costs

Oxygen-carrier particles:
- very encouraging results
- scale-up of particle manufacture
- raw materials
- long-term testing needed

Applications of chemical-looping combustion for CO_2 capture:

Combustion of gaseous fuel, natural gas, refinery gas, syngas

Chemical-looping reforming, i.e. hydrogen production

Combustion of solid fuels

Chemical Looping Combustion R&D Efforts of ALSTOM

Chemical Looping Combustion R&D Efforts of ALSTOM

Presented at the
IEAGHG International Oxy-Combustion Network
2nd Workshop
Windsor, CT USA

24-26 January 2007
Herb Andrus

Chemical Looping - Technology Development

Overview

- Chemical Looping – Objectives
- Chemical Looping – What is it?
  – What can it do?
- Economics
- Technical Aspects
- Projects/Test Facilities
- Development Program/Future Directions

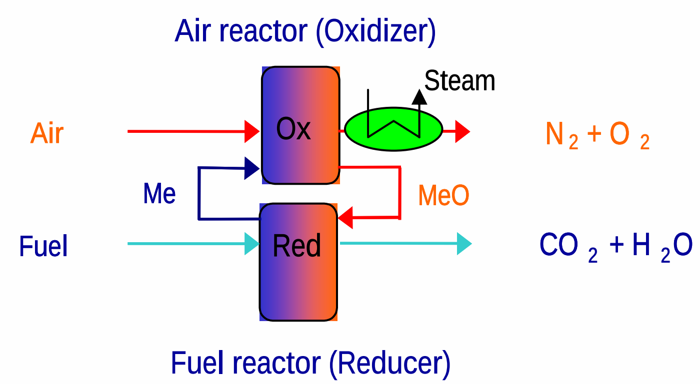
Chemical Looping:
a way to Capture CO_2 efficiently, at low cost

Objectives:

- Over 90% CO_2 capture from Coal
- Low avoided cost of CO_2 capture
- Capital cost – lower than CFB Boiler Island (without CO_2 capture)
- Competitive with Steam Power and IGCC on a world wide basis
- Medium Btu gas or Hydrogen without Oxygen Plant (Future)
- H_2 for Hydrogen economy (Future)

Chemical Looping Concept

- Why do it?: Lowest Cost Option for Capturing CO2 from Coal
- What is it?: Oxy-Firing without Oxygen Plant
  - Solid Oxygen Carrier Circulates between Oxidizer and Reducer
  - Oxygen Carrier: Carries Oxygen, Heat and Fuel Energy
  - Carrier picks up O2 in the Oxidizer, leaves N2 behind
  - Carrier Burns the Fuel in the Reducer
  - Heat producers Steam for Power
- Oxygen Carrier:
  - Metal Oxide: Fe, Ni, Mn, Cu…Ores or on Substrates
  - Limestone-based carriers
- Metal Oxides:
  - Process Development: CHALMERS UNIVERSITY
  - Equipment Development: ALSTOM
- Limestone-based: ALSTOM

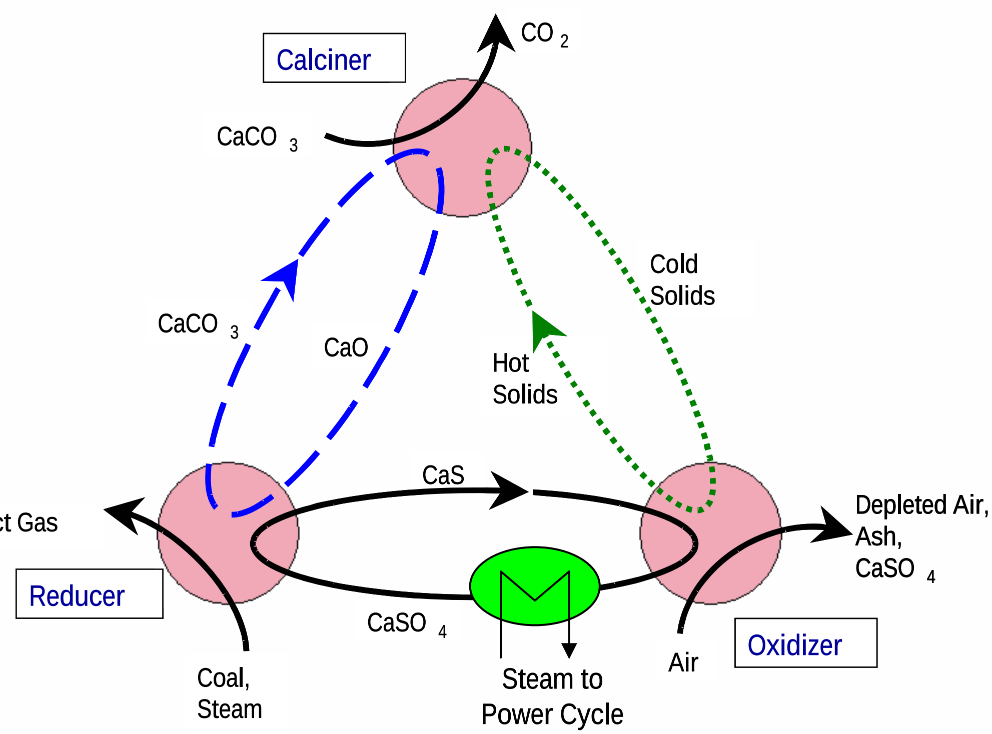


METAL OXIDE

Chemical Looping Concept

- Chemical Looping Flexibility
  - Option 1: **Chemical Looping Combustion**
    - Excess Air-to-Fuel
    - Product Gas is **CO2**
    - Heat Produces **Steam for Power**
  - Option 2: **Chemical Looping Gasification**
    - Excess Fuel-to-Air
    - Product gas is **SynGas**
    - No Inherent CO2 Capture
  - Option 3: **Hydrogen Production**
    - Add CaO – CaCO3 Loop to Option 2
    - Add Calciner
    - Product Gas is **Hydrogen**
    - Calciner Off-Gas is **CO2**

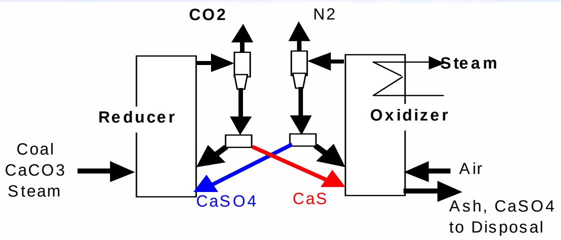
Limestone-based



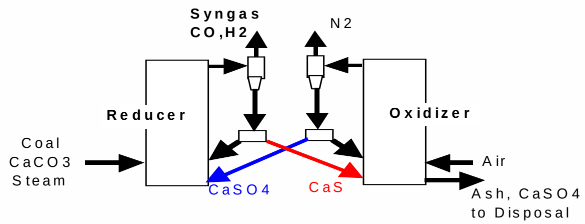
ALSTOM

Chemical Looping Flexibility

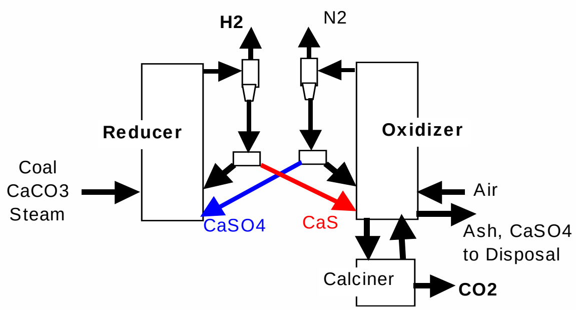
Several Related Processes can be Based on this Concept



- Option 1 – Combustion with CO2 Capture



- Option 2 – Syngas with no CO2 Capture

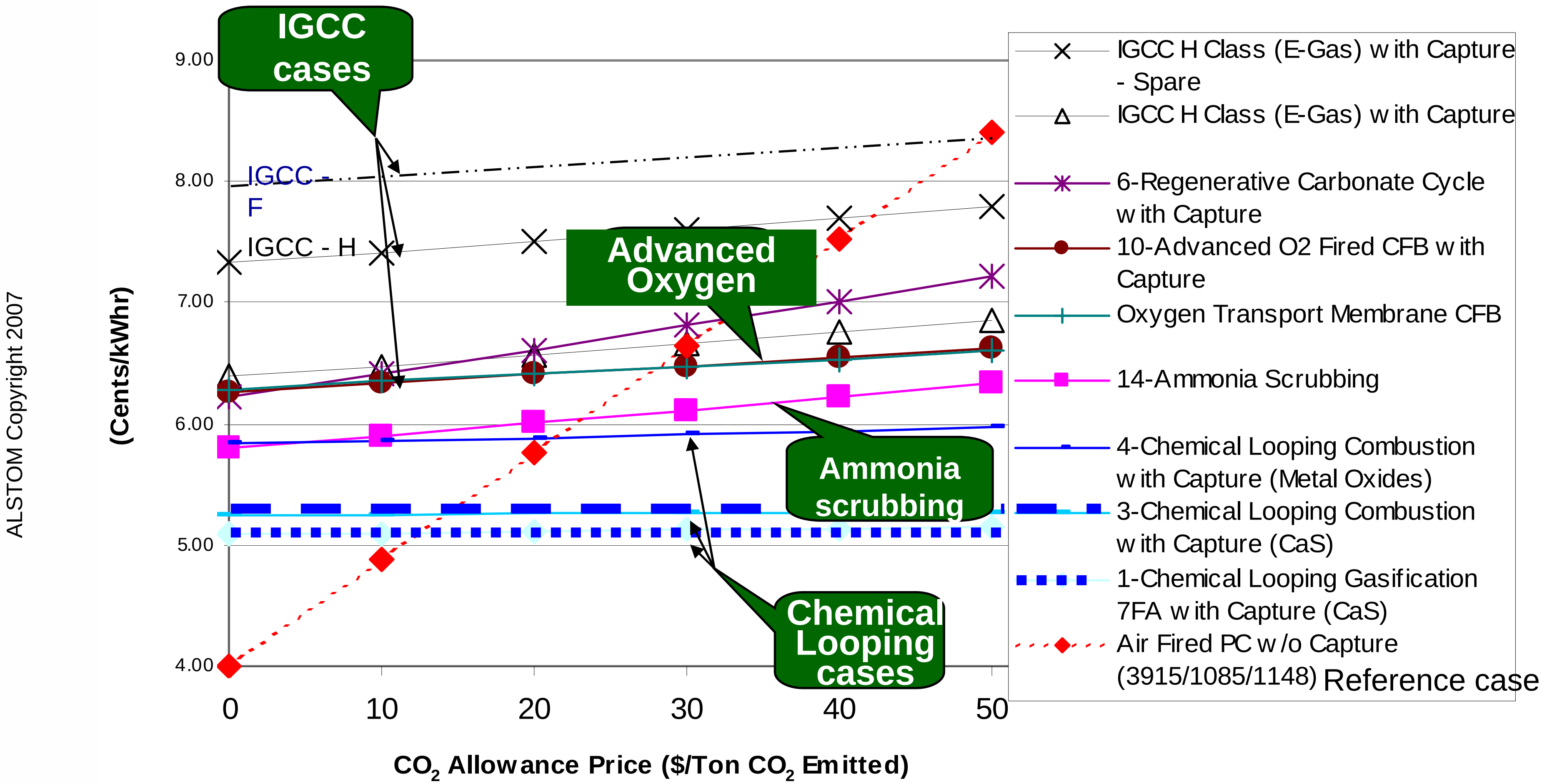


- Option 3 – Hydrogen with CO2 Capture

- Applications:
  - CO2 Capture-Ready Power Plant
  - Ultra Supercritical Steam Cycles
  - IGCC without Inherent CO2 Capture
  - CO2 Capture-Ready PC/CFB Power Plant
  - Advanced Steam Cycles
  - IGCC with CO2 Capture
  - Fuel Cell Cycles

- Lowest Cost CO2 Capture Option
- Competitive with or without CO2 Capture

CO2 Capture in Power Plants



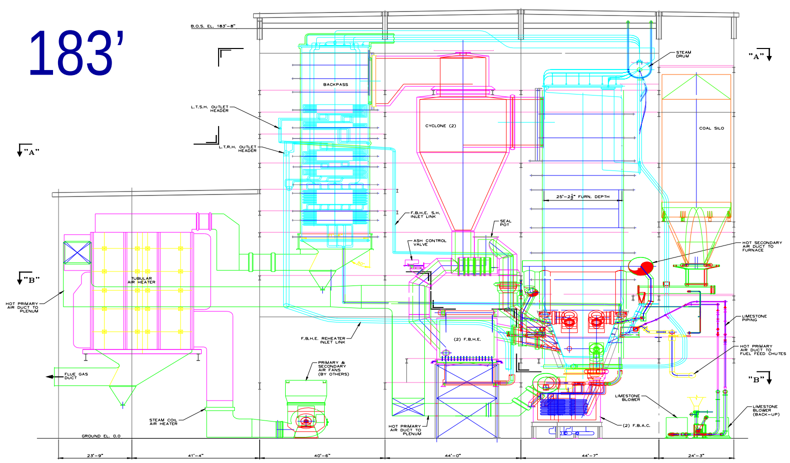
Chemical Looping CO2 Avoided Cost:
$11-13 per ton of CO2

Equipment Comparison

Significant Volume & Weight Reduction

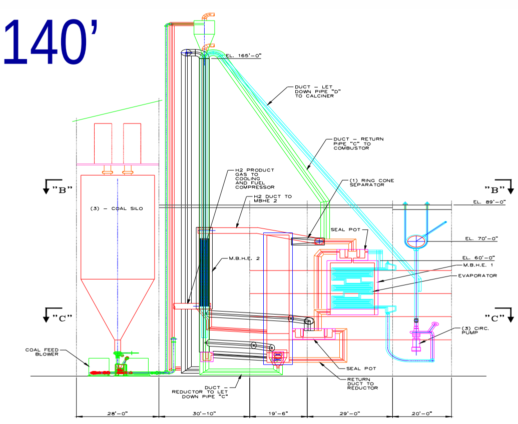
Air Fired CFB	Chemical Looping Gasifier

183'



220'

140'

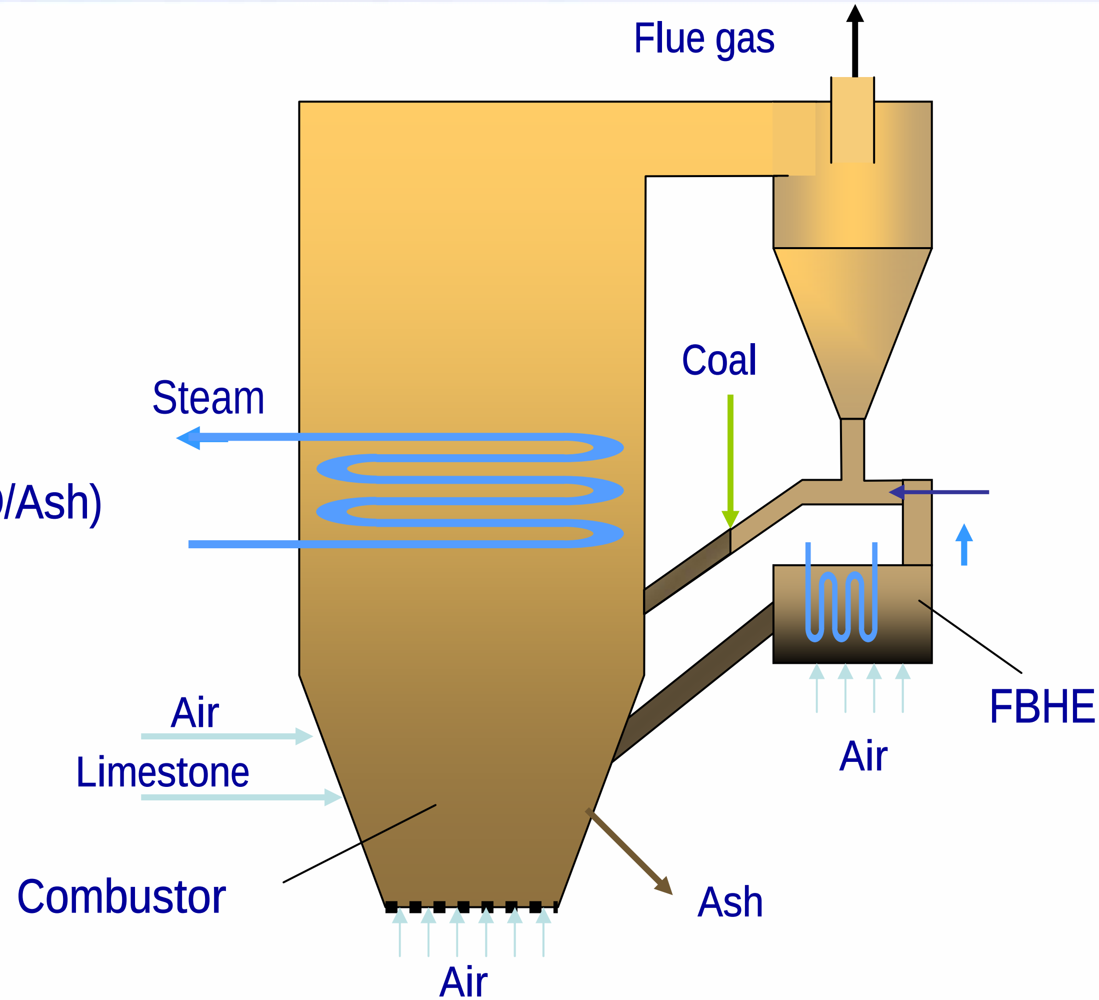


127'

Building Volume	100%	48%
Boiler/Gasifier Weight	100%	65%

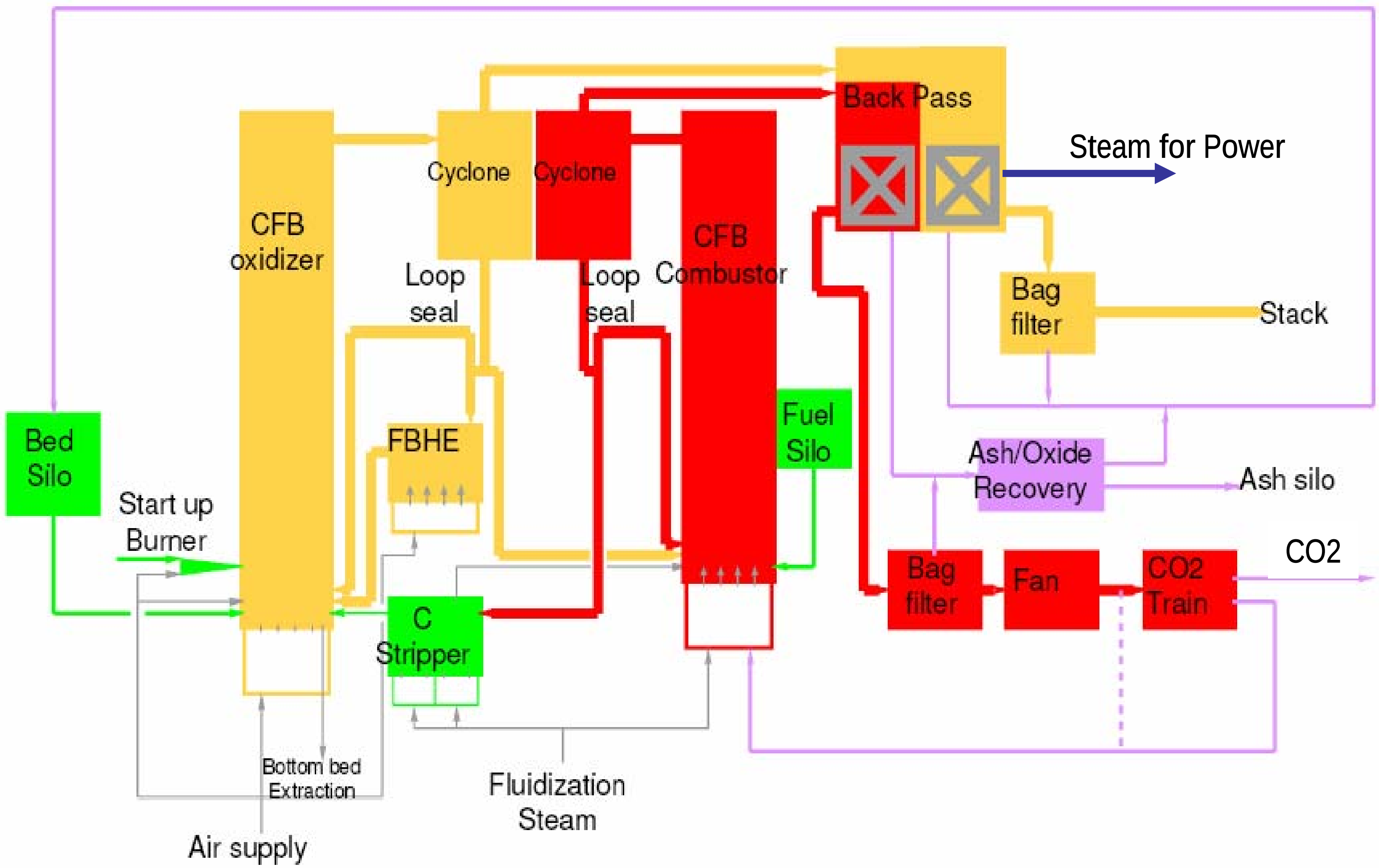
Circulating Fluidized Bed (CFB) - Principles -

- CFB Combustor
  - Fuel combustion
  - Sulfur capture using limestone
- Fluid Bed Heat Exchanger (FBHE)
- CFB/FBHE Characteristics
  - High Solids Loading ($CaSO_4/CaO$/Ash)
  - Uniform bed temperature
- Well suited for Chemical Looping
  - High Heat/Mass Transfer Rates



Chemical Looping – Builds on ALSTOM's CFB Technology

Chemical Looping Combustion with CFB for solid fuels



Chemical Looping features

- Process characteristics
  - Near 100% CO_2 capture
  - Many potential Oxygen Carriers:
    - (Fe,Ni,Mn,Cu,...with various supports; Limestone)
  - No Oxygen Plant
  - No energy penalty for oxygen production and for CO_2 separation
- Performance requirements
  - Reactive and attrition resistant oxygen carrier
  - Sufficient solids flow , typical of CFB solids transport
  - No gas exchange between the two reactors

Oxygen Carrier Criteria

Selection of oxygen carrier:

- High reactivity under oxidizing and reducing conditions
- Able to fully convert Fuel to CO_2 and H_2O
- Long life expectations without attrition
- No agglomeration under operating conditions of temperature (760 to 1050°C; 1100 to 1900°F)
- Manufacture at low cost
- Resistant to fuel chlorine and sulfur degradation

ALSTOM Chemical Looping Projects

		Fuel	
Application	**Sorbent**	**Natural Gas**	**Coal**
Combustion	MeO	EU – CLC Gas Power	EU – ENCAP
	CaO		U.S. DOE Hybrid Combustion/Gasification
Gasification	MeO	EU – Cachet	
	CaO		U.S. DOE Hybrid Combustion/Gasification

Joint Governmental / Industrial Sponsorship

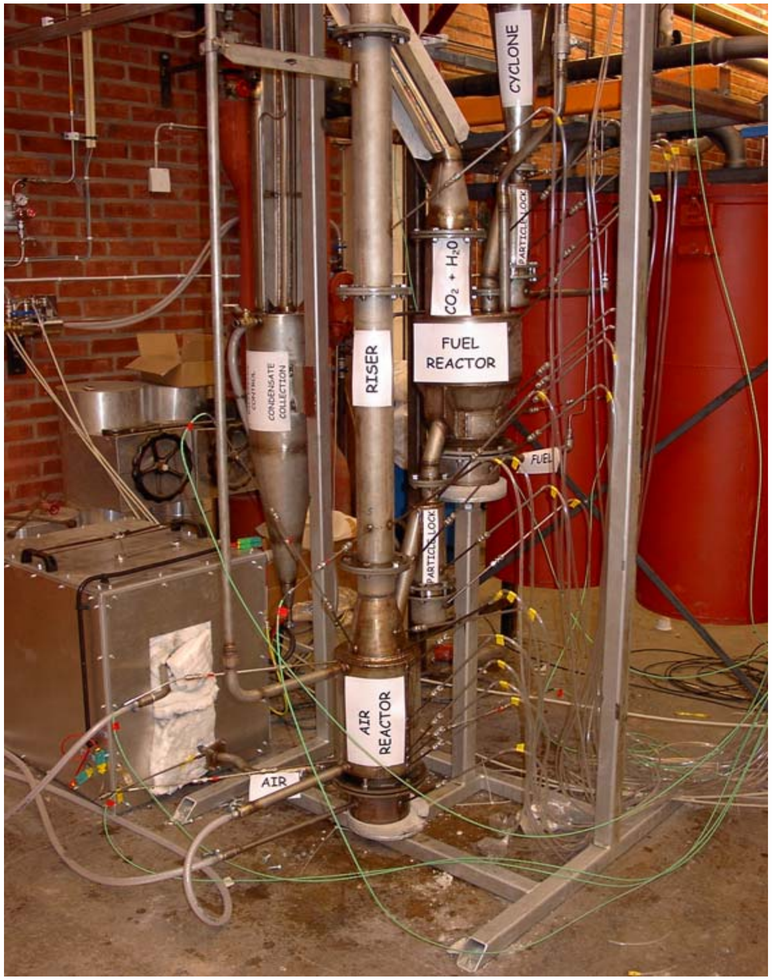
Chemical Looping
Process Development Unit

Chalmers University –300 Wt PDU

- Carrier Performance Screening
- Agglomeration
- Attrition
- Preliminary Kinetics

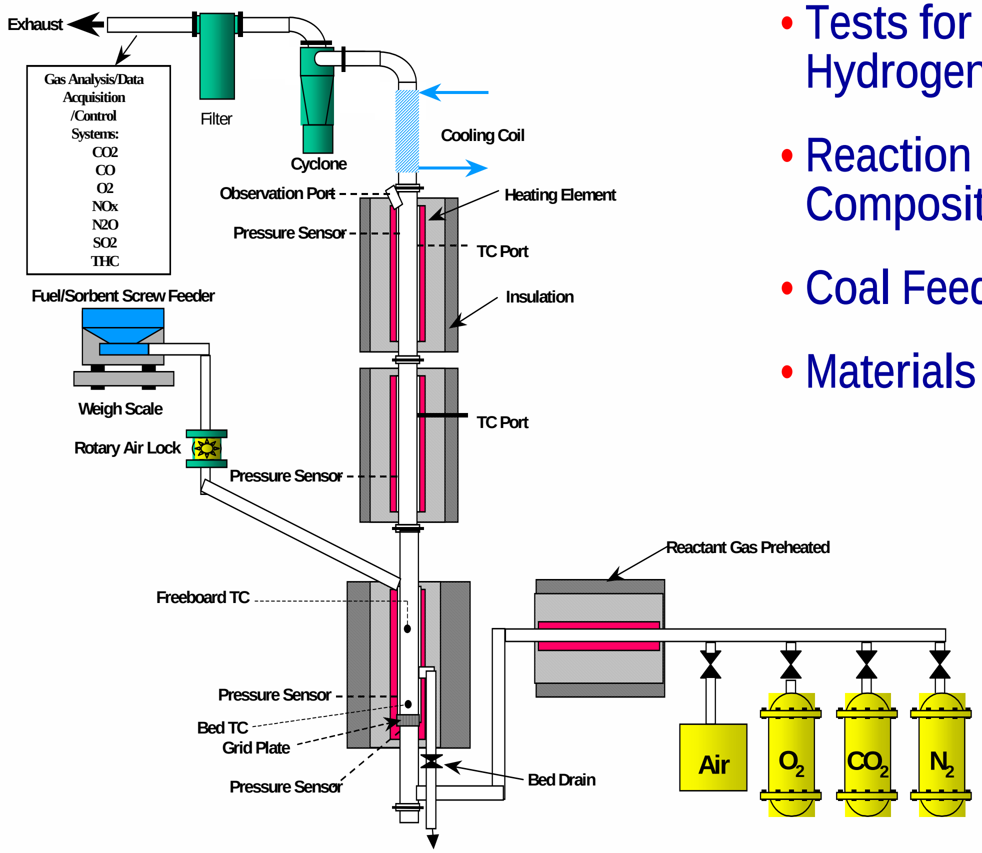
MeO Chemical Looping Pilot

Chalmers University -10 kW pilot



- Long term Testing
- Many MeO's Tested
  - Low Cost Ores
  - Manufactured Carrier Particles
- Cold Flow Tests for Solids Transport
- Natural Gas and Solid Fuels
  - Coal
  - Petcoke

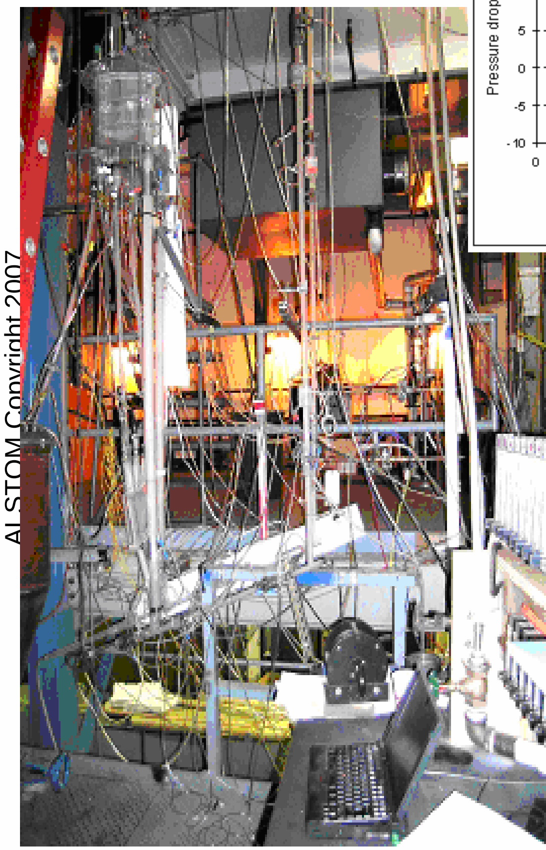
ALSTOM - 4 Inch Fluid Bed Reactor System

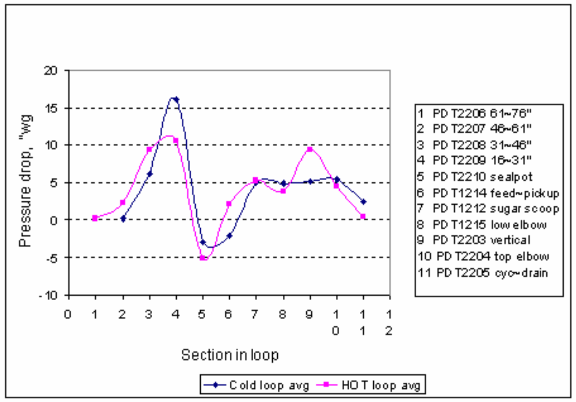


- Tests for CO2 Capture, Water-Gas Shift, Hydrogen production
- Reaction Rates Over a Wide Range of Temps and Compositions
- Coal Feed and Coal Pyrolysis Tests
- Materials Handling Tests

ALSTOM - Cold Flow Model Testing

15 Foot Model

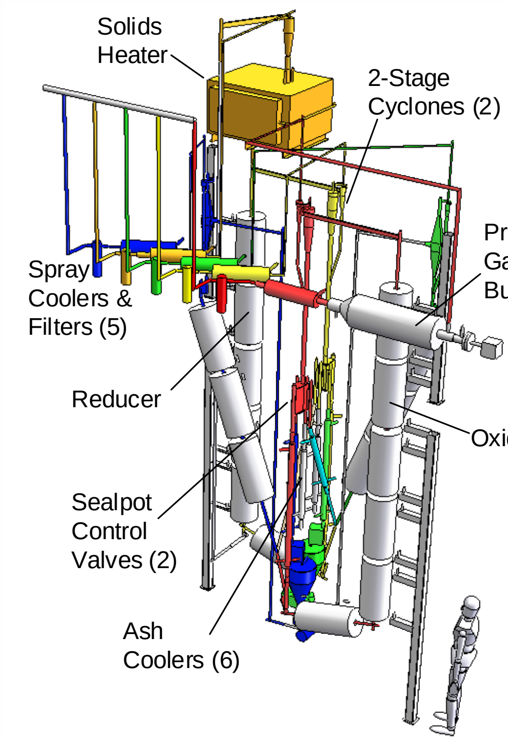




Laser Solids Velocity Probe

40 Foot Model

ALSTOM - Chemical Looping Program
Process Development Unit



- Chemical Looping Process Development Unit
- Designed and Built by Alstom
- Allows Testing of Individual Loops and Processes
- 2 Year Successful Test Program – Completed
- All Chemistry / Rates Verified
- Phase 3 - Pilot Plant
  - Two Exhaust Fans/Stacks
  - Automatic Solids Transport Controls

ALSTOM

Chemical Looping Combustion: The Way Forward

Prototype: for Autothermal Operation and System Integration

Demonstration: Scale-up Similar to CFB (20 – 70 MW)

Retrofit Potential: Pulverized Coal and CFB

Supercritical Steam Cycles

600°C (1100 °F) → 700 °C (1300 °F)
Mitigates CO2 liquefaction penalty

Advanced Cycles – IGCC, Fuel Cells, Industrial Hydrogen

ALSTOM - Chemical Looping

SUMMARY

- Chemical Looping – **lowest cost** option for CO2 Capture
- Compatible with Advanced Supercritical Steam Cycles
- Suitable for CO2 Capture-Ready PC and CFB Boilers
- Future Cycles include IGCC, Fuel Cell Cycles
- SynGas and Hydrogen for Industrial use

ALSTOM

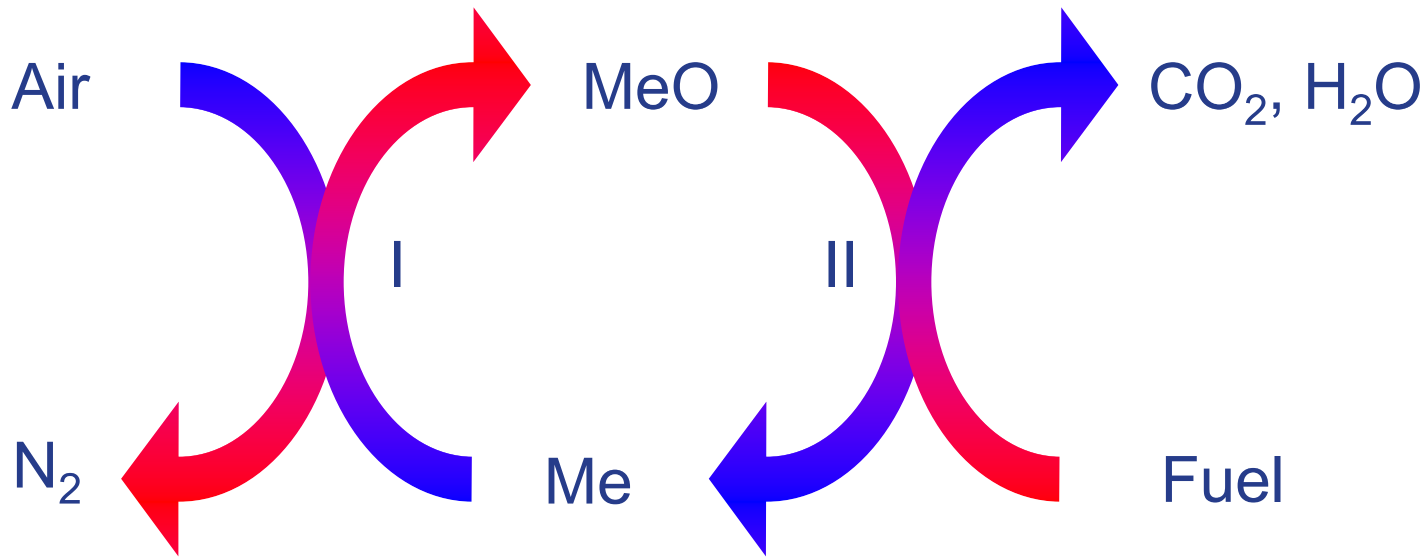
www.alstom.com

Packed Bed Reactor Technology for Chemical-Looping Combustion

S. Noorman, M. van Sint Annaland, J.A.M. Kuipers (UT)
N.A.M. ten Asbroek, P.H.M. Feron (TNO)

2nd IEAGHG Oxyfuel Combustion Workshop
25th and 26th of January 2007, Windsor, USA

Chemical-looping Combustion



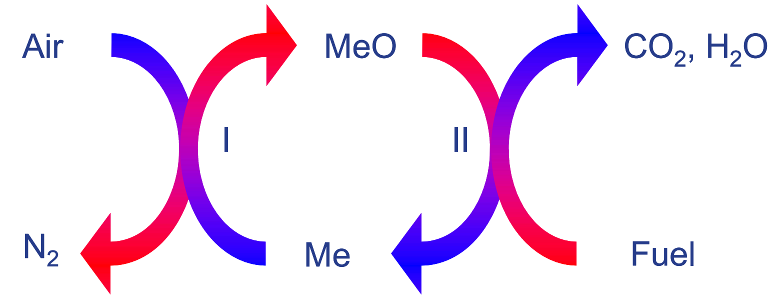
I: $4\ Me + 2\ O_2 \rightarrow 4\ MeO\ (\Delta H < 0)$

II: $4\ MeO + CH_4 \rightarrow 4\ Me + CO_2 + 2\ H_2O\ (\Delta H > 0)$

- Power production with inherent CO_2 separation
- Direct contact between air and fuel is avoided

Introduction

- Chemical-looping Combustion:
  - Potential for very high CO_2 capture efficiency
  - No energy penalty for separation
  - No NO_x formation
  - Direct implementation in power plants is challenging



I: $4\ Me + 2\ O_2 \rightarrow 4\ MeO\ (\Delta H < 0)$

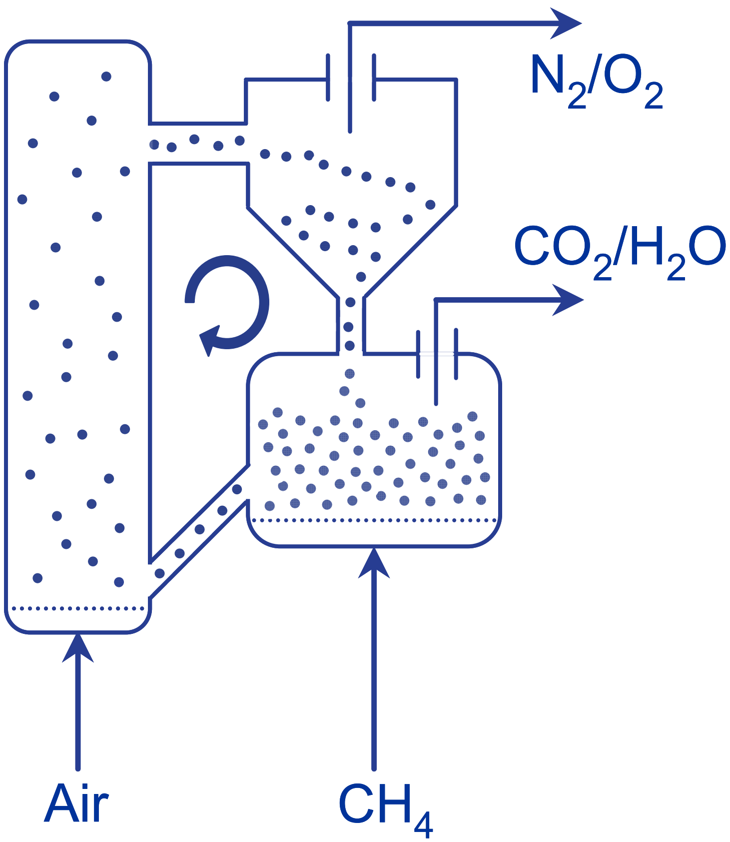
II: $4\ MeO + CH_4 \rightarrow 4\ Me + CO_2 + 2\ H_2O\ (\Delta H > 0)$

- Important research themes:
  - Oxygen carrier (MeO = NiO, Fe_2O_3, Mn_3O_4, CuO)
  - Implementation in power plant
  - Reactor concepts

Oxidizing and reducing conditions must be imposed alternately

Reactor Concepts

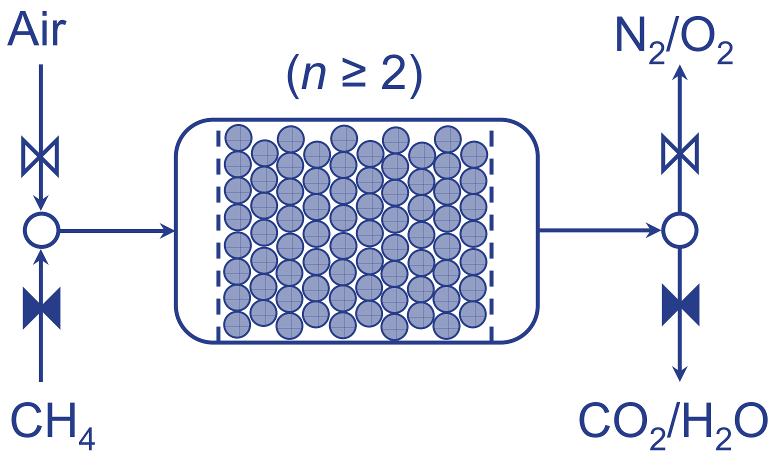
Recirculation or stationary solids?



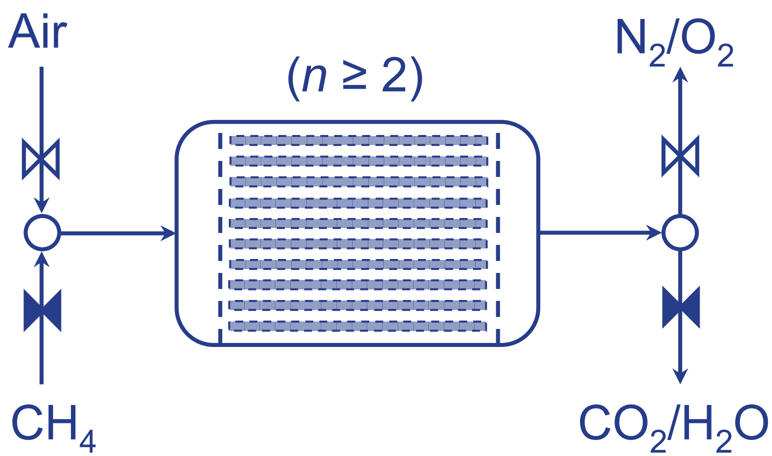
- Disadvantage of fluidization:
  - Recirculation of particles
  - Difficult gas-solid separation (formation of fines)
- Packed bed (membrane-assisted) CLC:
  - Stationary solids
  - Periodic switching of gas streams
  - Dynamically operated parallel reactors (gas switching system)
  - Natural gas → combined cycle!

Packed Bed CLC

- Packed bed CLC (UT):



- Packed bed membrane-assisted CLC (TNO):



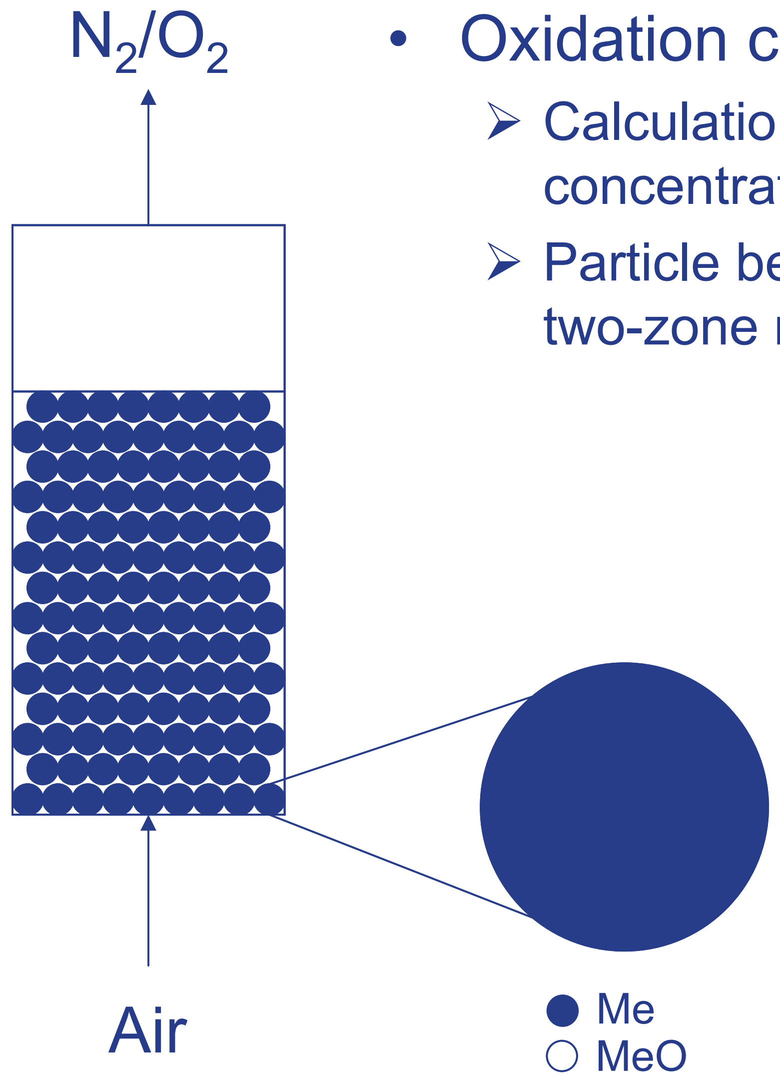
- Process demands:
  - ➢ Constant high-temperature air stream
  - ➢ High overall and CO_2 capture efficiency
  - ➢ Continuous operation
  - ➢ Extreme conditions (T_{out} = 1300-1500 K, p = 20-30 bar)

Project Goal

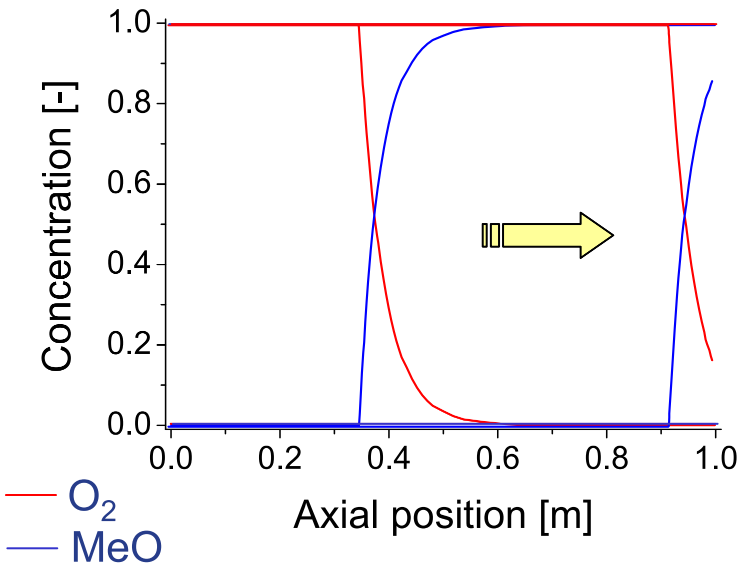
- Evaluation of the feasibility of packed bed CLC as an alternative power production technology:
  - ➢ Can CLC be carried out using packed bed (membrane-assisted) technology?
  - ➢ How can packed bed CLC with an optimal overall energy efficiency be realized?
  - ➢ How does packed bed CLC perform, compared to fluidized bed CLC and other CO_2 capture processes?

- This presentation:
  - ➢ Modeling and experimental work on packed bed CLC.

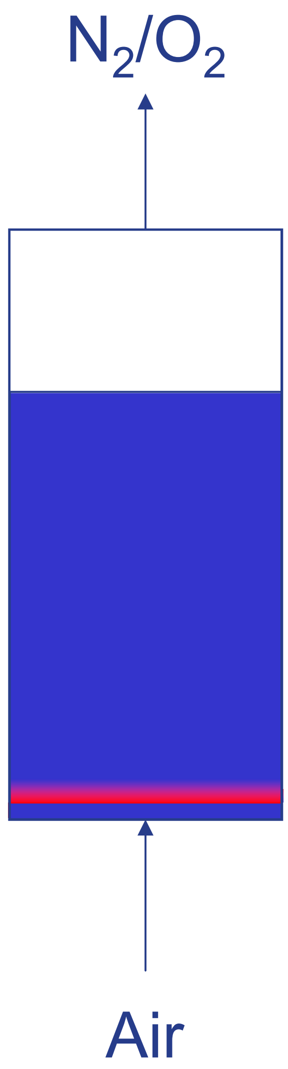
Packed Bed CLC: Oxidation



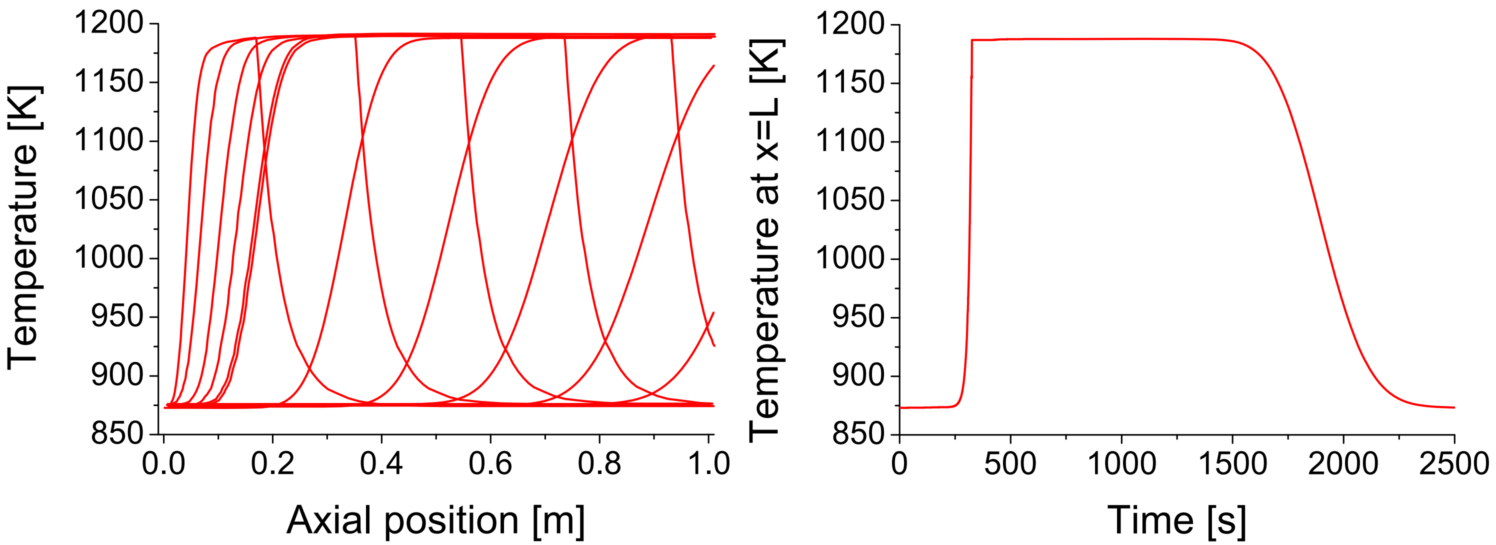
- Oxidation cycle:
  - Calculation of axial temperature and concentration profiles.
  - Particle behavior is described using a two-zone model



Packed Bed CLC: Oxidation



- Oxidation cycle:
  - ➢ Temperature evolution



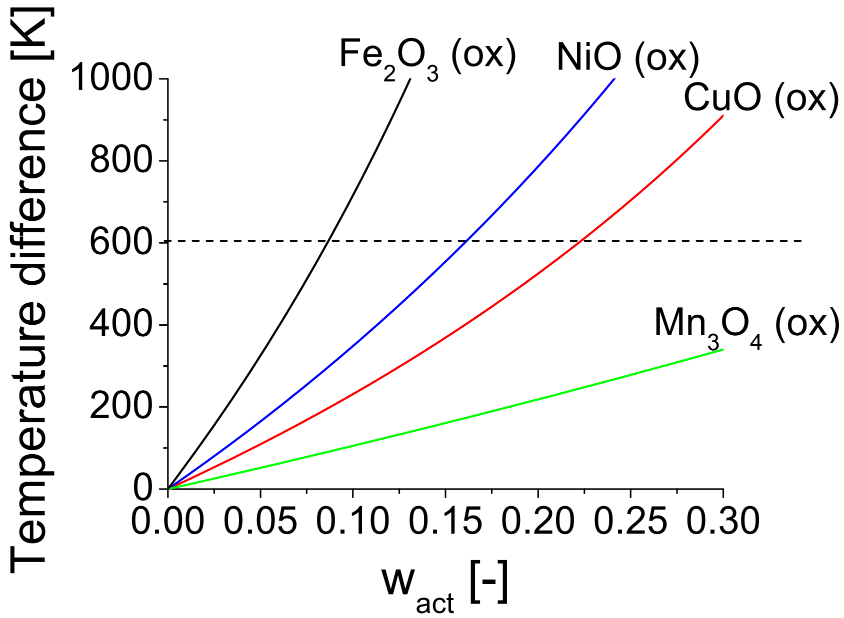
- 'No' influence of reaction kinetics or flow rate
- An air stream of high, constant temperature is produced → gas turbine

Oxygen Carrier Properties

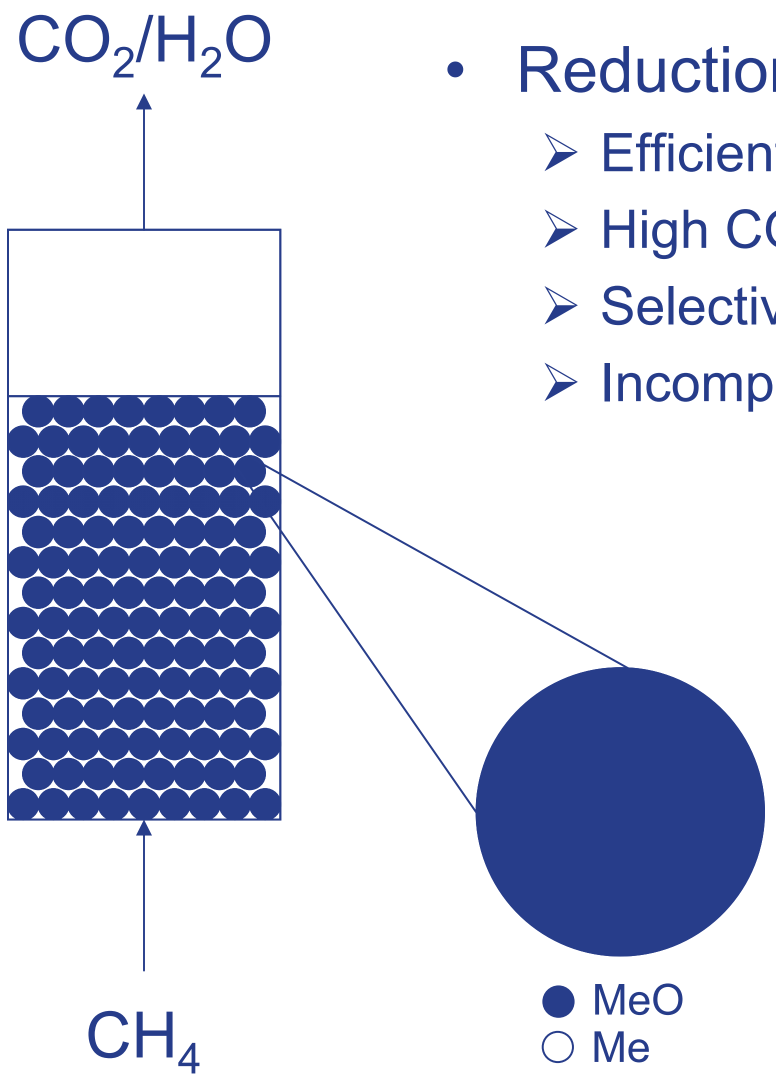
- Analytical approximation:
  - Infinitely high reaction rate
  - No influence of conduction

$$\Delta T = \frac{(-\Delta H_R)}{\dfrac{C_{p,s} M_{act}}{w_{act}\,\xi} - \dfrac{C_{p,g} M_{O_2}}{w_{g,O_2}^{in}}}$$

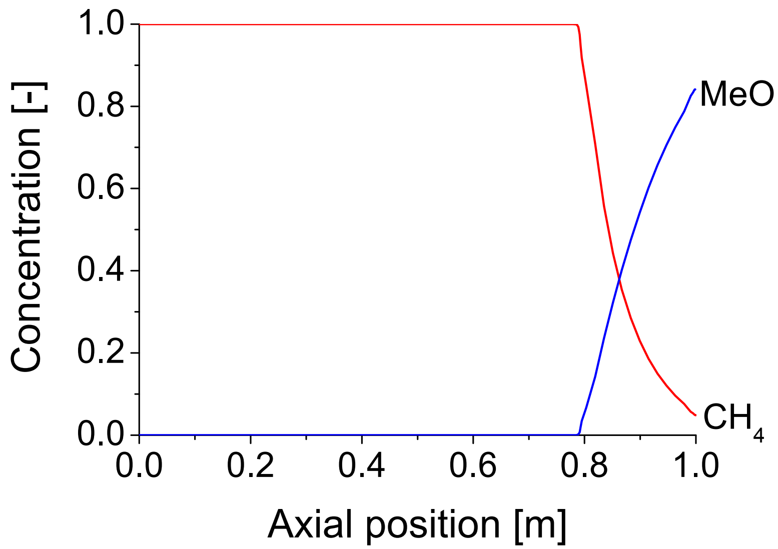
- Temperature increase can be tuned:
  - Active content
  - Support material
  - Oxygen concentration



Packed Bed CLC: Reduction

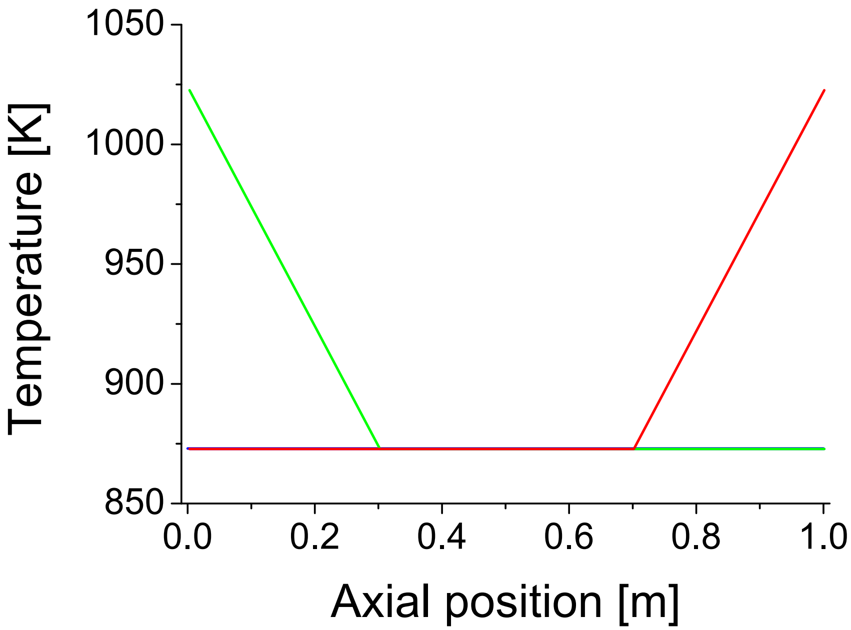


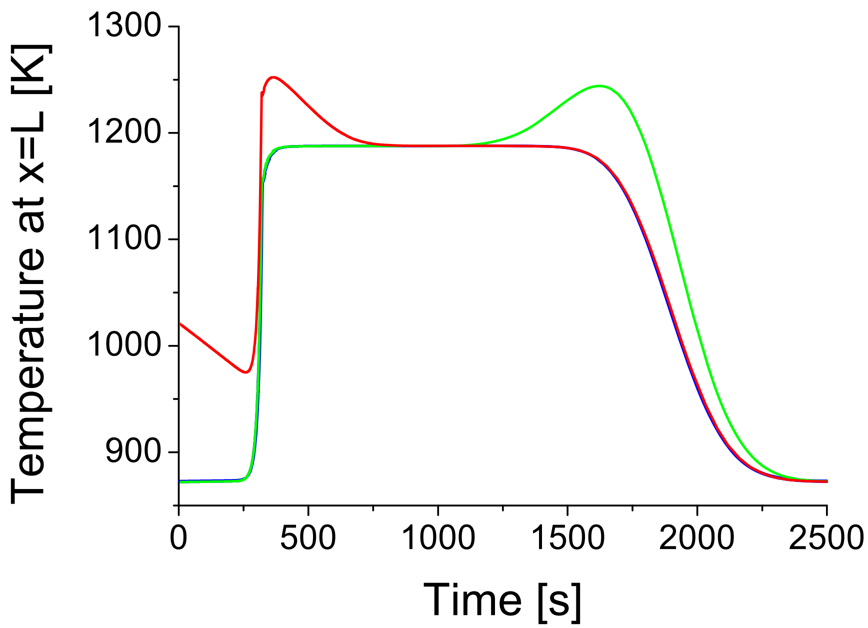
- Reduction cycle:
  - Efficient use of fuel
  - High CO_2 capture efficiency
  - Selectivity to CO_2 and H_2O
  - Incomplete regeneration of part of the bed



Packed Bed CLC: Operation

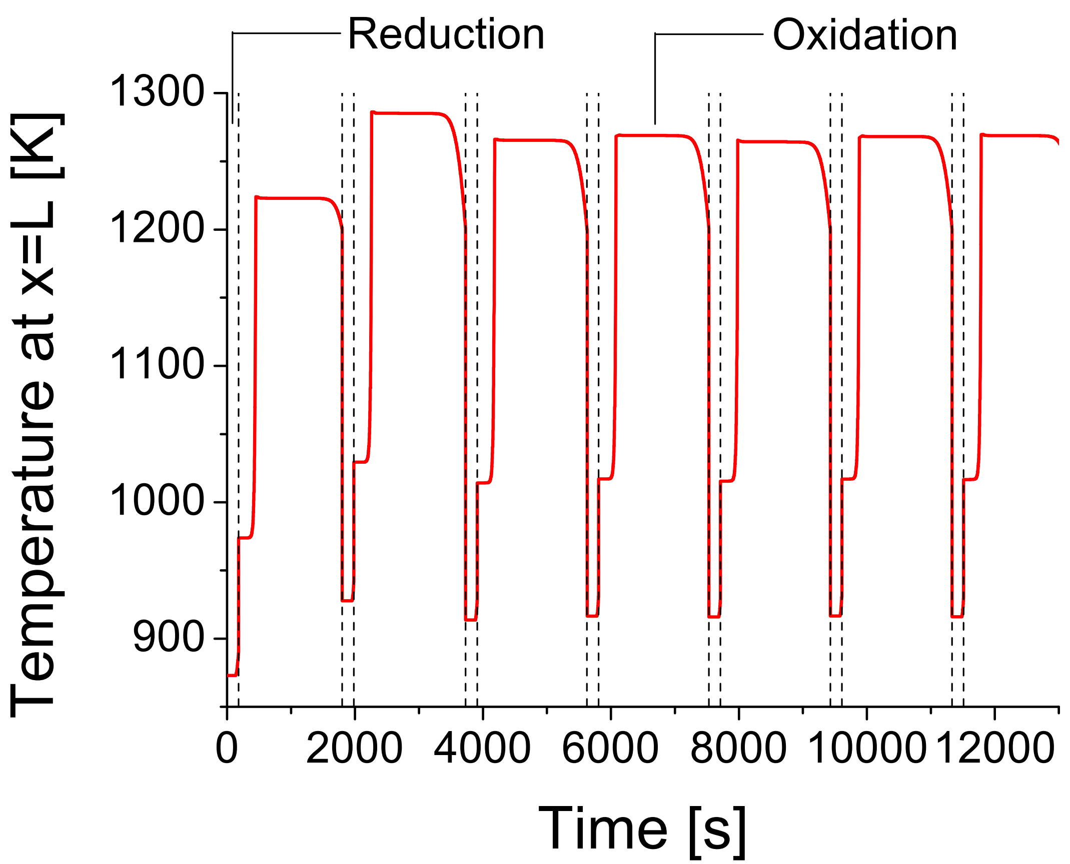
- Operation over multiple cycles:





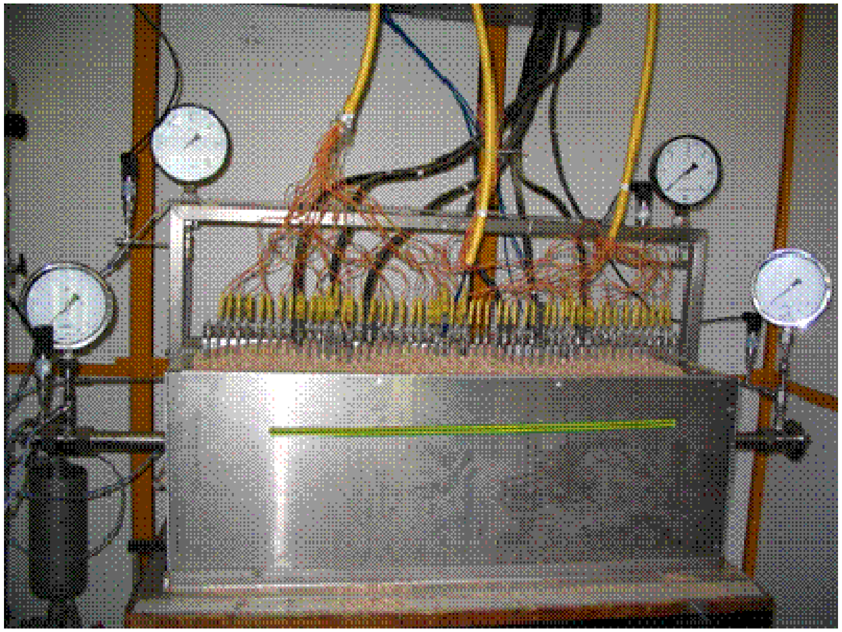
➢ Fluidization between oxidation and reduction cycles is necessary to level off temperature profiles.

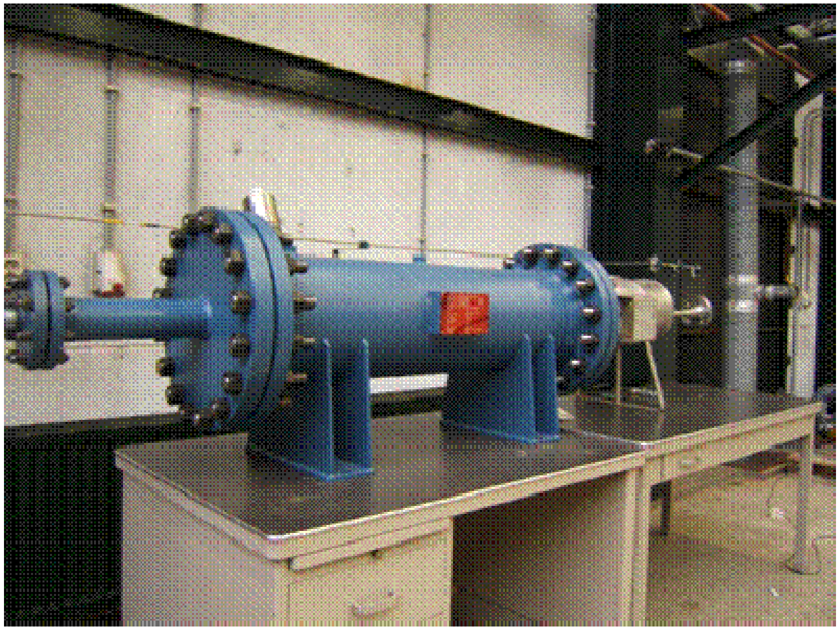
Modeling Packed Bed CLC

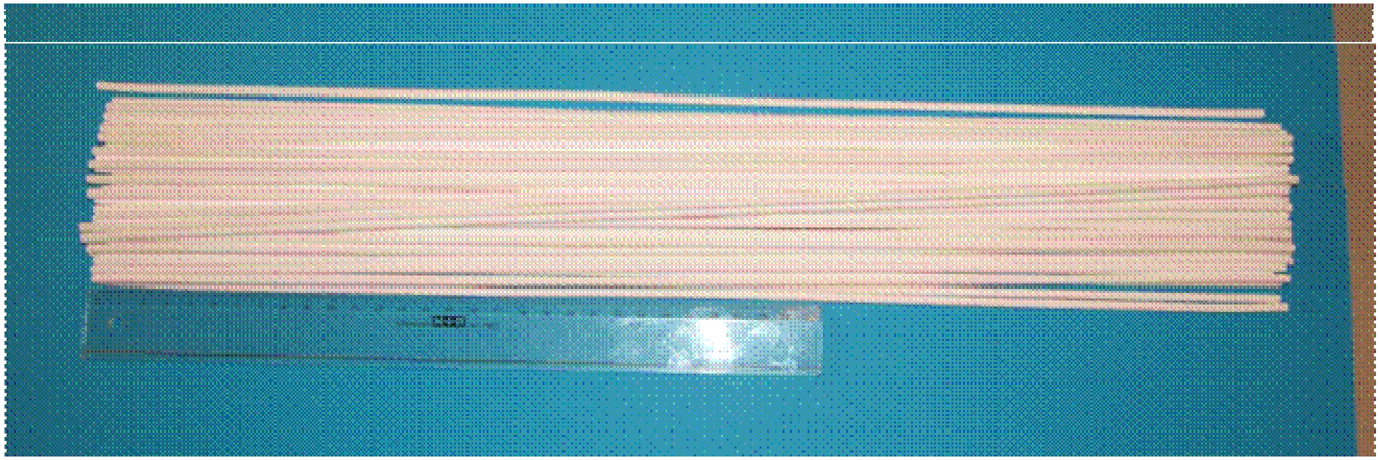


→ Cyclic steady state is obtained after only a few oxidation/reduction cycles.

Experimental Validation

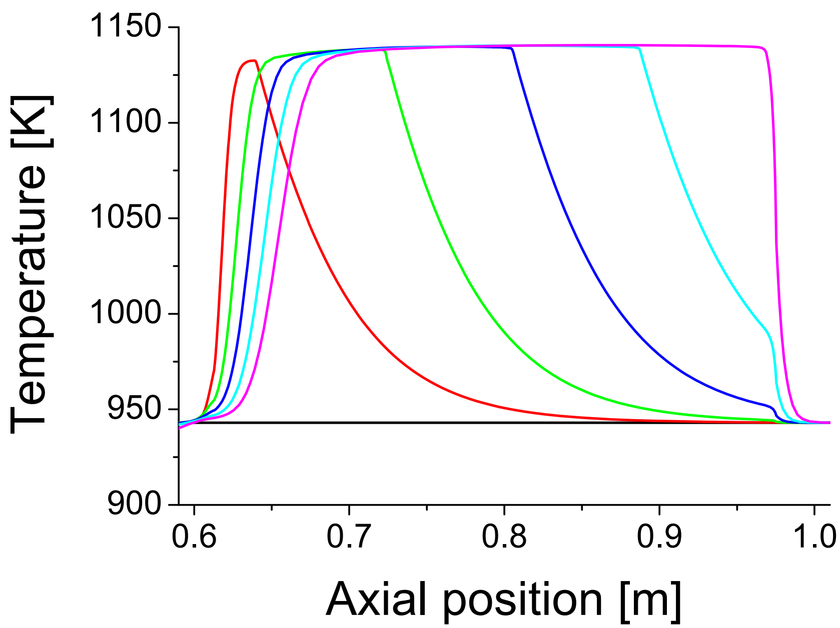




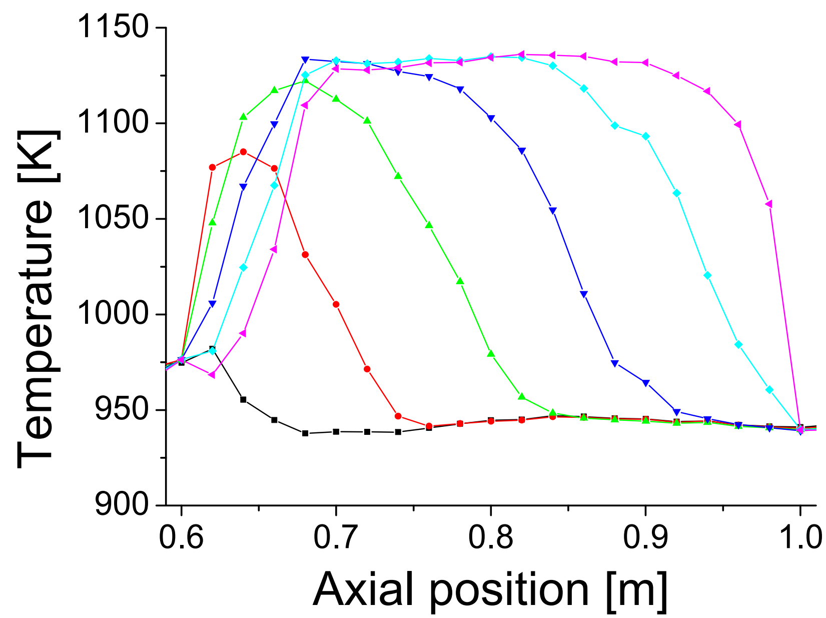


Experimental Validation

Model description



Experimental results



(t = 0, 6, 12, 18, 24, 30 s)

Oxidation reaction: (Cu/CuO, $w_{act} \approx 0.1$)

Improvements:

- Correct implementation of heat losses in the model
- Coupling of particle model and reactor model

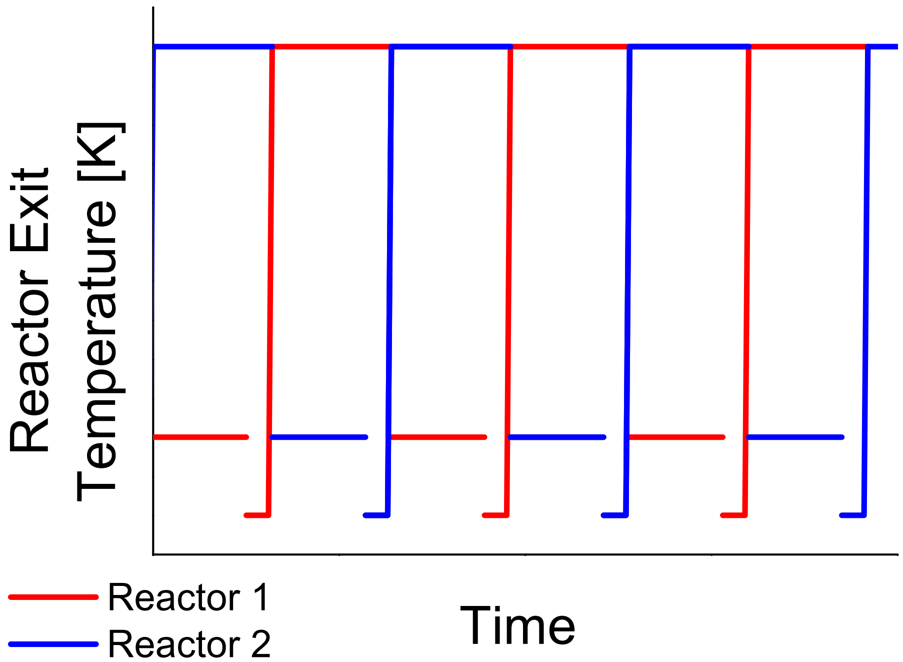
	Model	Exp.	
ΔT_{max} [K]	195	199	✓
w_2 [cm/s]	1.53	1.58	✓
w_1 [cm/s]	0.13	0.15	✓

Implementation

- Implementation in power plant:
  - Combined cycle to maximize overall energy efficiency

- Process design:
  - Pressure drop
  - Number of reactors
  - Reactor sizing
  - Heat integration, etc.

- Important features:
  - Compact design
  - Suitable for part-load operation



Conclusions

- Packed bed (membrane-assisted) CLC is an interesting alternative power production technology:

- Process operation:
  - Oxidation cycle: generation of high temperature air stream
  - Reduction cycle: combining efficient use of fuel and high CO_2 capture efficiency

- Implementation in power plant:
  - Combined cycle

- Future work:
  - Experimental validation of packed bed CLC
  - Process design and efficiency calculations

Clean
Energy
Systems

Coal-Based Oxy-Fuel System Evaluation and Combustor Development

Leonard Devanna

Clean Energy Systems, Inc.

IEAGHG Oxy-Combustion Workshop, 25-26 January 2007

Clean Energy Systems

Outline

- Introduction: CES oxy-combustion technology
- Development of CES oxy-combustor for natural gas applications: *from 110 kW_t bench-scale unit to 20 MW_t operating power plant to 200 MW_t now being built*
- Development of CES technology for coal applications
- California coal power initiative
- So. Cal Gas/CES Press Release: CA ZEPP-1, commercial operations 2008/9
- Early stage company bias

Clean
Energy
Systems

Who We Are

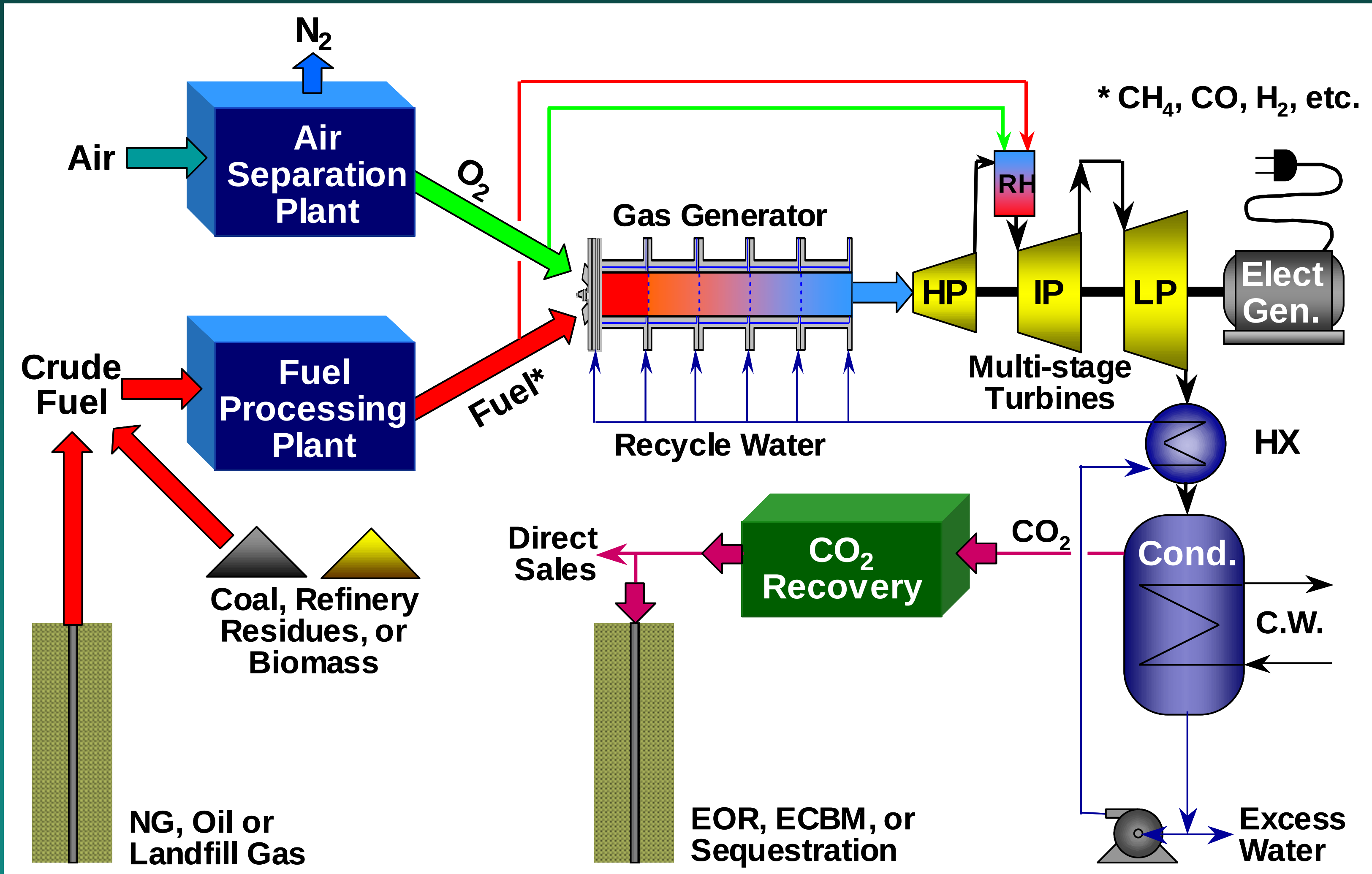
- CES founded in 1993 in Sacramento, CA by aerospace engineers. Incorporated in 1996.

Who We Are (2)

- 23 issued patents on zero-emissions oxy-combustion power cycles.
- We own and operate a 20 MW_t demonstration power plant in California.
- We focus on intellectual property (IP) rights and we manufacture the “enabling technology” – the oxy-combustor.
- Strong Investors AES and Sempra

Clean Energy Systems

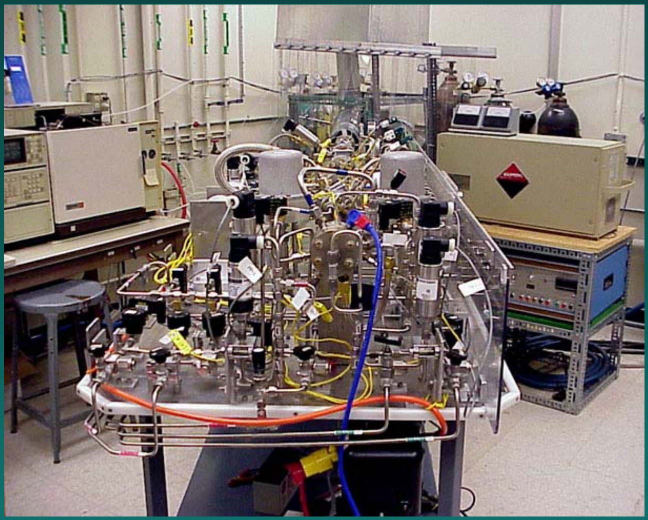
The CES Process

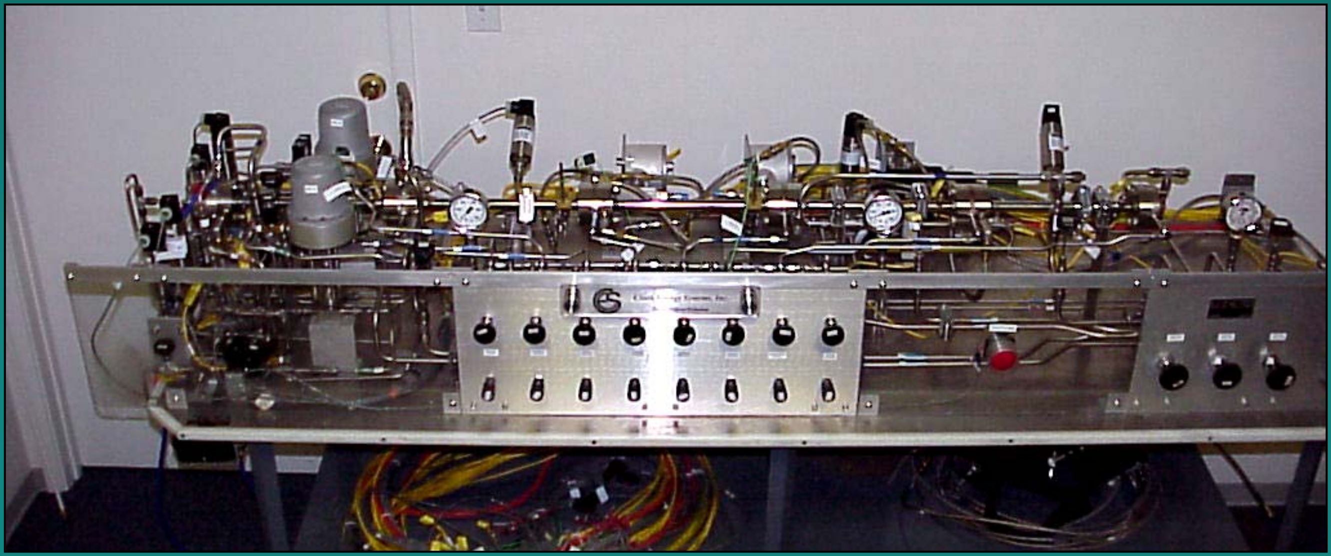


Clean Energy Systems

Milestone 1: 110 kW_t Bench-Scale Combustor

- Funded in part by the California Energy Commission (CEC)
- Demonstrated “proof of principle” on bench-scale combustor with complete control system
- Testing successfully completed in January 2001





Clean
Energy
Systems

Milestone 2: 20 MW_t Combustor

- CES awarded $2.5 million (of $3.7 million project) in Sept. 2000 under DOE/NETL Vision 21 program
- Designed, fabricated and tested a 20 MW_t combustor with CH_4 as fuel
- Operating pressure of 100 bar and temps from 650-1650ºC
- Testing completed Feb. 03
- 100 starts and durations up to limit of test facility

Clean Energy Systems

Milestone 3: Zero-Emissions Power Plant Demonstration

- In 2002 CEC awarded CES $2 MM to demonstrate its combustion technology in nat. gas-fired power plant
- CES acquired 5 MW Kimberlina power plant in Aug. 2003.
- In Nov. 2003 CEC approved Kimberlina location and provided supplemental $2.4 MM funding

Kimberlina 5 MW Test Facility and Power Plant

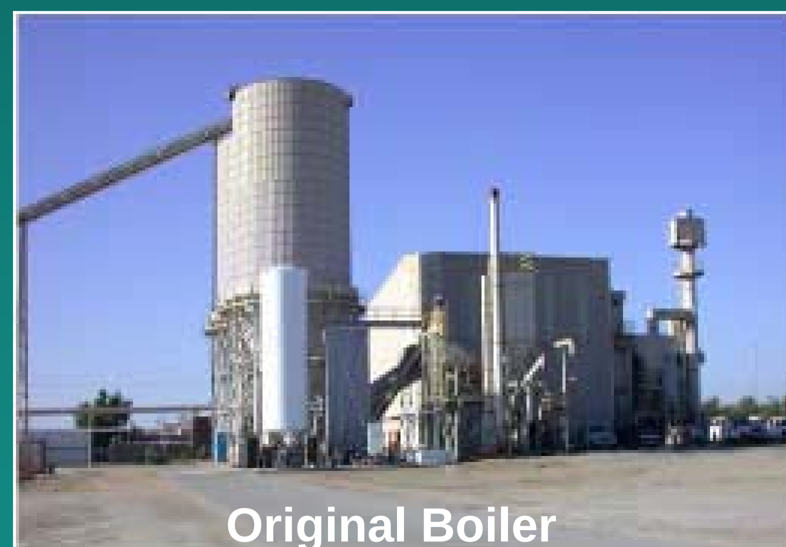
pier · NETL · AIR LIQUIDE · MIRANT

Clean
Energy
Systems

Kimberlina Combustor and Power Plant

20 MW_t Combustor

5 MW_e Steam Turbine



Original Boiler

Clean Energy Systems

Oxy-Syngas Combustor Development

- DOE awarded CES $4.6M to develop oxy-syngas combustion technology
  - Three year project, started 10/1/05
  - Using coal-derived syngas and H_2-depleted syngas
  - With CO_2 capture
- In collaboration with Siemens Power Generation, Inc.
  - $14.5M DOE funding for first two phases of their project
- Partners and Subcontractors: Siemens Power Generation, Siemens Fuel Gasification (*was Future Energy*), Air Products, GC Broach, Kinder-Morgan

Outline of Oxy-Syngas Program

Clean Energy Systems

- Phase I (completed)
  - Performed process modeling on current (2006), near-term (2010), and long-term (2015) coal-based cycles
  - Installed syngas blending station at Kimberlina
  - Modified Kimberlina combustor for syngas operation and tested at 5 MW_t (4 in.) on simulated syngases
- Phase II (underway)
  - Detailed design of 50 MW_t (12 in.) syngas combustor
  - Fabrication of syngas injector (core component of combustor)
- Phase III (future)
  - Fabrication of remaining combustor components
  - Testing at Kimberlina or at third party location

Clean Energy Systems

Syngas Testing at Kimberlina

- Blending station installed to supply simulated syngas
- Combustor modified for syngas operation
  - Fuel delivery system modified for low-BTU fuels
  - Control system expanded
  - New oxy-syngas combustion injector installed
- Parametric testing completed (4 in.)
  - Fuels: Syngas and H_2-depleted syngas
  - Power levels: 2.3 to 4.7 MW_t
  - Combustion pressures: 220 to 340 psia (15 to 23 bar)
- Test data being used to prepare detailed design of 50 MW_t (12 in.) syngas combustor

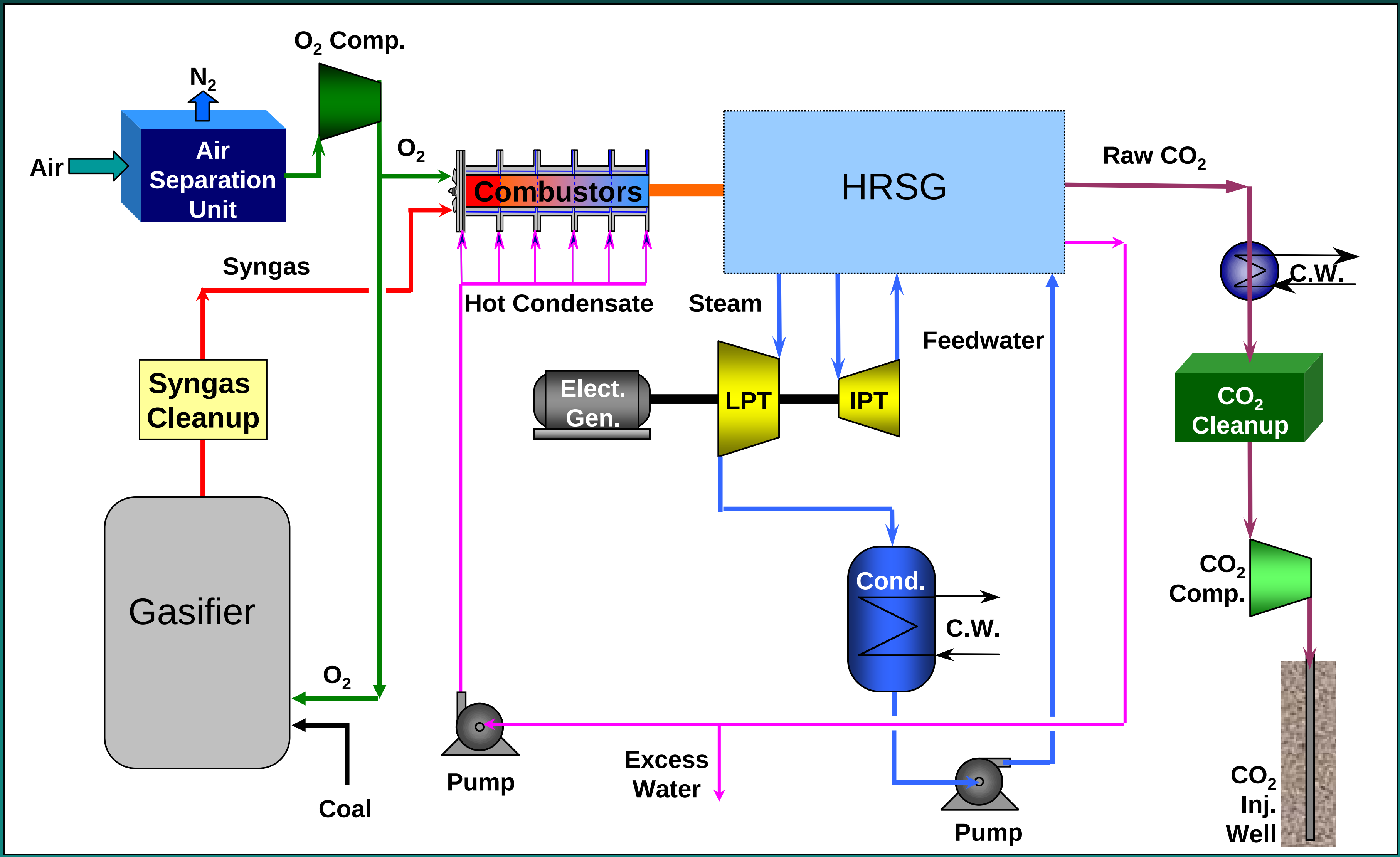
Clean
Energy
Systems

Syngas Testing at Kimberlina

Kimberlina Power Plant during syngas testing. CO and H_2 tube trailers in foreground

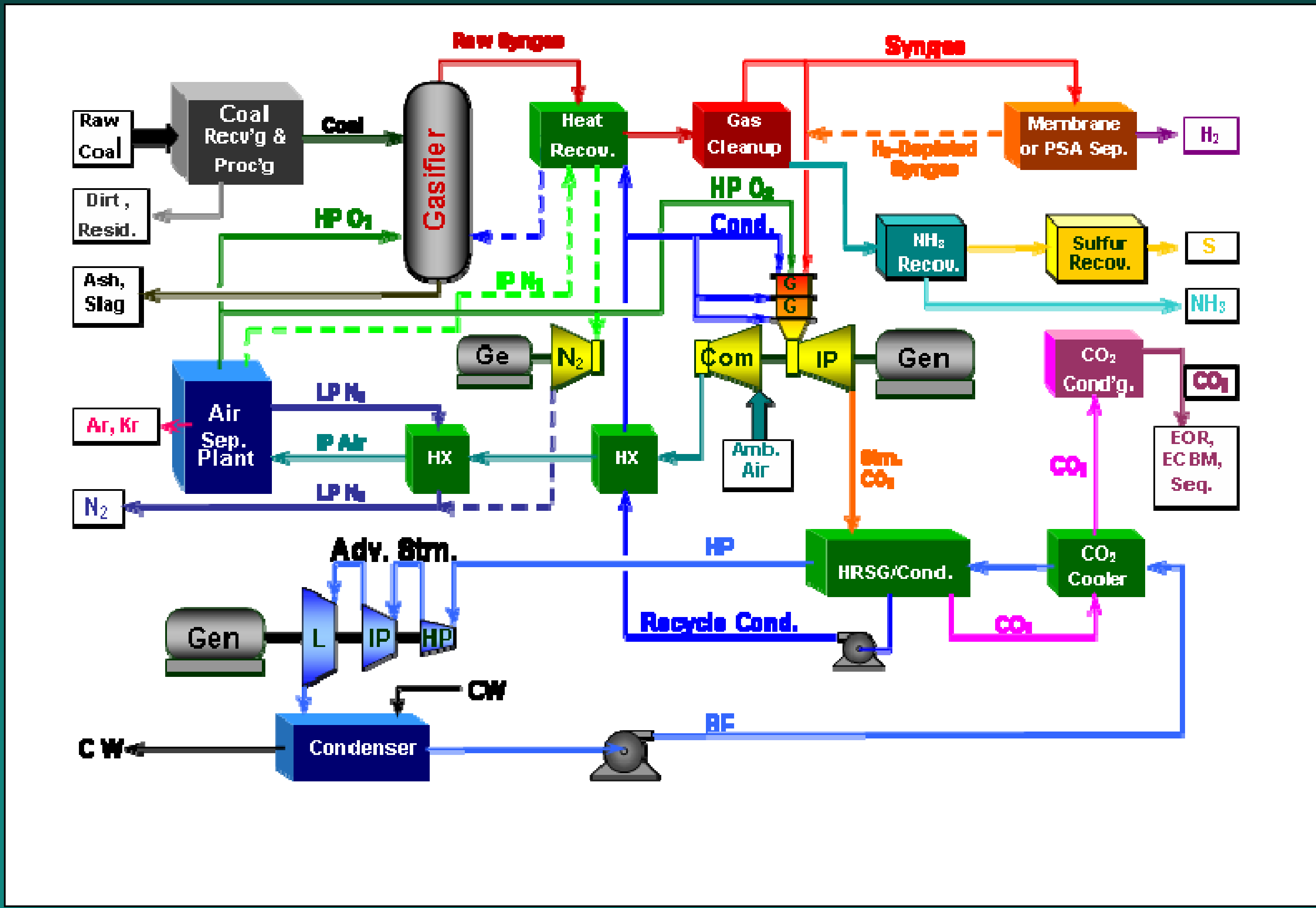
Clean
Energy
Systems

CES First Generation Integrated Gasification (IGCES) Plant



Clean Energy Systems

CES Second Generation Integrated Gasification (IGCES) Plant



Clean
Energy
Systems

CPUC Interim Opinion on GHG Standards

- Interim GHG performance standards
- Reduce CA's financial risk to future compliance costs
- Financial risk also includes cigarette co. scenario
- Applicable to new/renewed purchase power contracts that are not CCGT and greater than 60% LF
- Max allowable emissions: 1,000 lb CO_2 /MWH
- Applicable to each unit, no averaging
- No coal in CA without carbon capture
- Opportunity!, Opportunity!, Opportunity!

Clean
Energy
Systems

Possible GHG Reduction Portfolio

- Renewable Portfolio Standard, (***Sequestration model***)
  - Eligible Sources: Solar, Photovoltaics, Wind, etc.
  - Price: \$0.06-\$0.16/kwh
  - Standard: Increase 2%/yr beginning in 2003 to 20% by 2010; 33% by end of 2020
- GHG Reduction Portfolio
  - Eligible Sources: Hydrocarbon fueled facilities assuming a base EPS of (1,000 lbs CO_2/MWh)
  - Standard: Starting in 2010, 1% of hydrocarbon portfolio must have an 85% reduction from the existing EPS of a CCGT (150 lbs CO_2/MWh)
  - Increasing by 1%/yr through 2015

Clean
Energy
Systems

California ZEPP-1

(Zero Emission Power Plant)

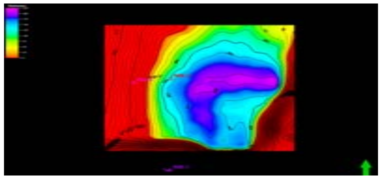
- So. Cal. Gas/CES Press Release
- 45-50 MW
- May be part of WestCarb
- Commercial sale of electricity and CO_2
- Electricity: $.06-$.11/KWH; CO_2: $20-$30/ton
- Late 2008, early 2009 commercial operations

Clean
Energy
Systems

Conclusions

- CES oxy-combustor operated for >1,300 hours on natural gas at Kimberlina
- Combustor successfully tested with simulated syngas at power levels up to 5 MW_t
- CES designing 50 MW_t pre-commercial syngas combustor
- First commercial coal-based offering would be CO_2 production plant with 200 MW_t IGCES plant
- CA coal restrictions may be followed by other states
- Utility GHG Portfolio req. can drive the technology
- Political process will accelerate zero/near zero emissions opportunities

CO2 CAPTURE → CO2 TRANSPORT AND INJECTION → CO2 STORAGE



The Oxy-Combustion and CO_2 Storage Pilot Plant Project at Lacq

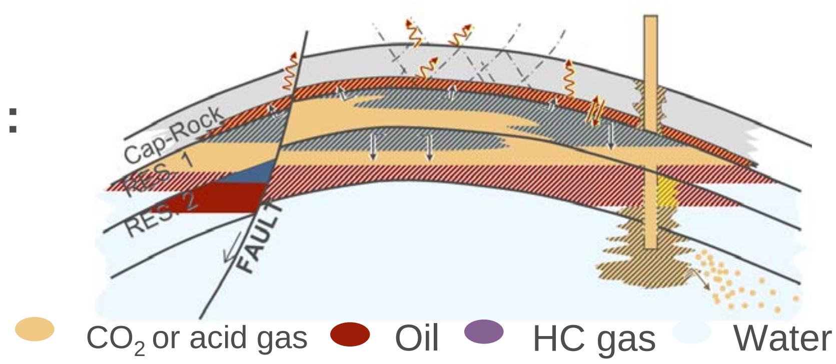
IEA GHG Oxy-Combustion Network Workshop
Jan. 26th, 2007

TOTAL

Total Exploration & Production involved in CO_2 Capture and Storage

- **A portfolio of options to reduce green house gas emissions :**
  - Gas flaring reduction (world bank GGFR) on existing facilities
  - Improve power efficiency
  - CCS as breakthrough technology

- **Dedicated CCS program since 2001 :**
  - Capture technology development
  - CO_2 and acid gas injection
  - Storage and well integrity
  - Long tem fate of CO_2, monitoring

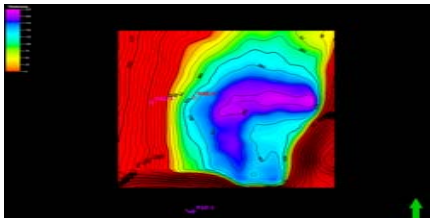


TOTAL

Lacq pilot general objectives

- An integrated CO2 Capture, Transportation, Injection and Storage pilot plant

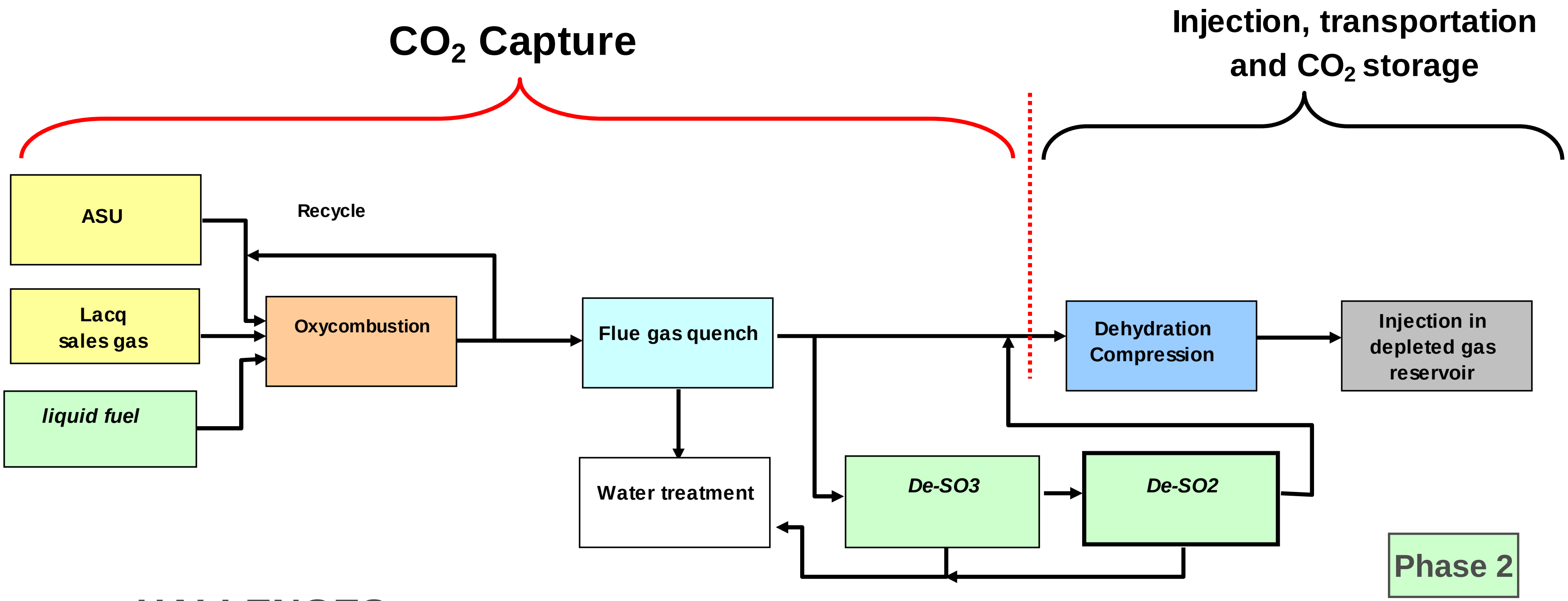
CO2 CAPTURE → CO2 TRANSPORT AND INJECTION → CO2 STORAGE



- Contribute to a climate change option among other mitigation actions
- Assess the technical feasibility and reliability of a cost attractive full carbon capture and storage scheme adapted to steam generation
- Basis for Extra Heavy Oil (bitumen) hot production upscaling (steam assisted production)
- CO2 storage into a depleted reservoir pilot (modelling, monitoring)
- Assess the Lacq field potential for long term and larger scale CO2 storage

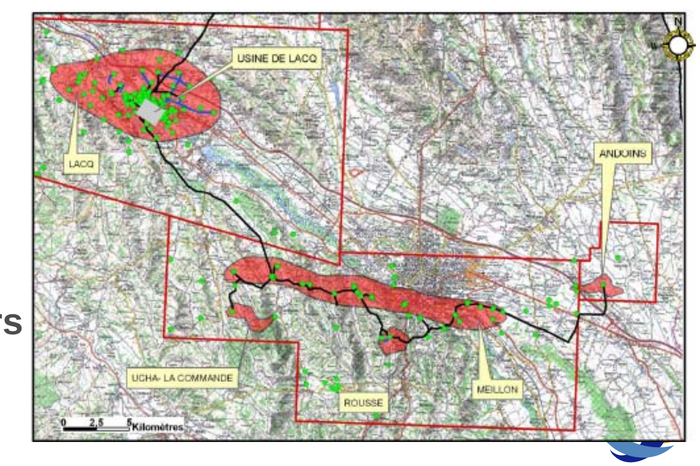
TOTAL

CCS Lacq pilot to start end 2008

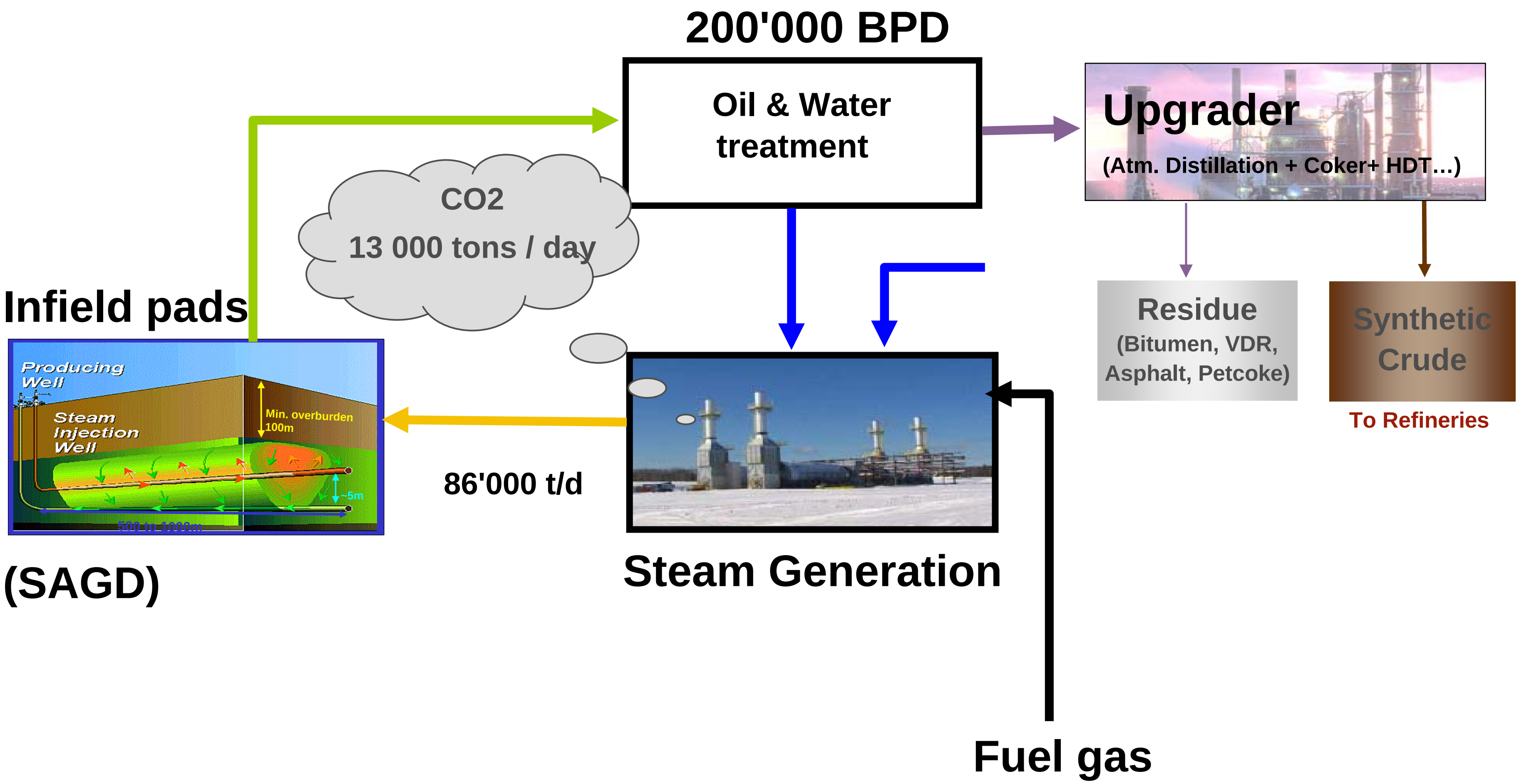


CHALLENGES

- ✓ Industrial scale 30MWth oxycombustion unit with gas
- ✓ Revamping of a 35MW+ conventional boiler
- ✓ High sulfur liquid fuel to be tested in second phase
- ✓ First CO2 injection for storage in France
- ✓ No french nor international legal framework yet
- ✓ CO2 transport and injection into a Lacq satellite for 2 years
- ✓ 150 kt CO2 storage in a depleted reservoir

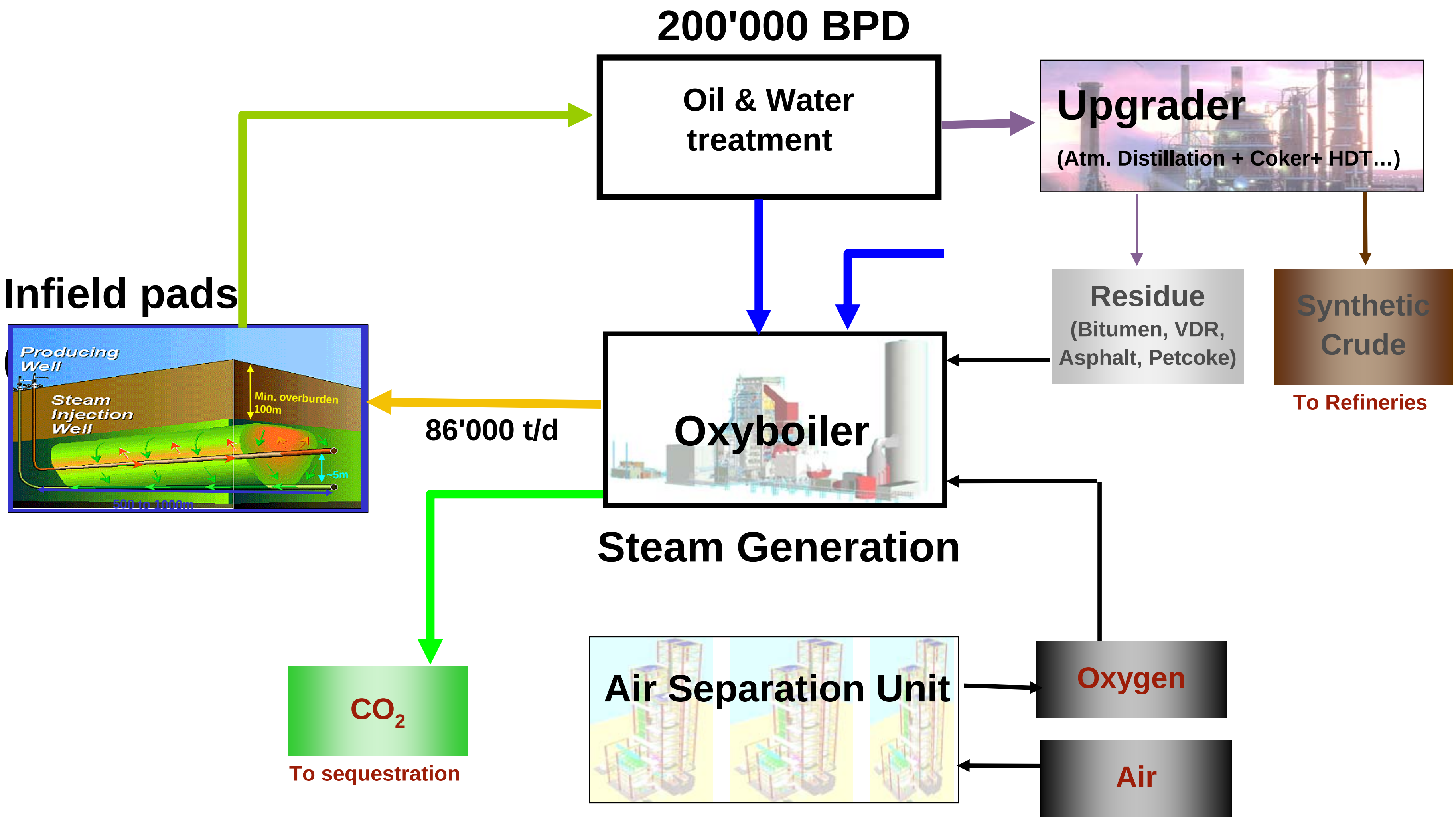


Example of Extra Heavy Oil production with steam injection



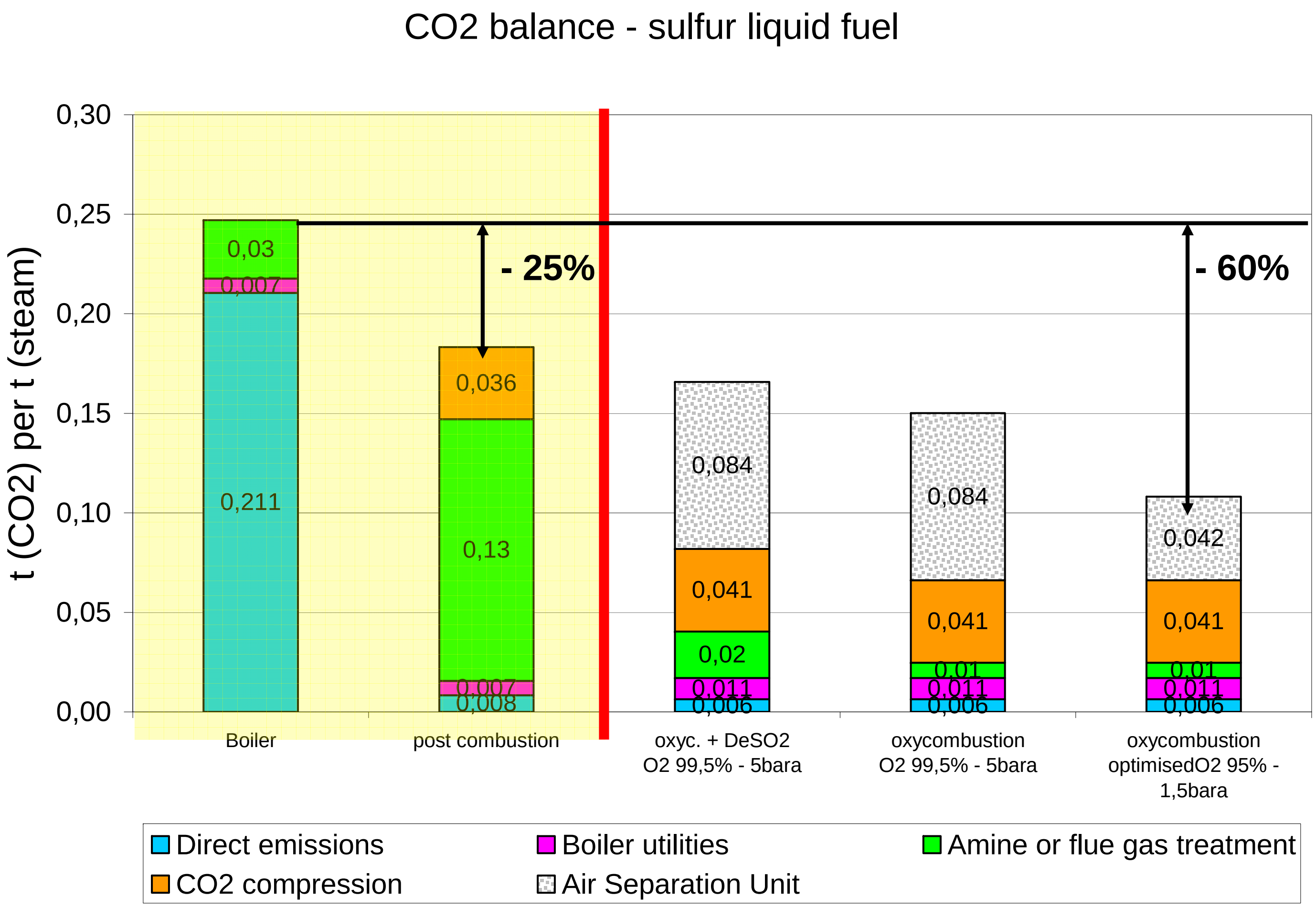
TOTAL

Oxycombustion as capture technique EHO production Total and Air Liquide studies since 2003



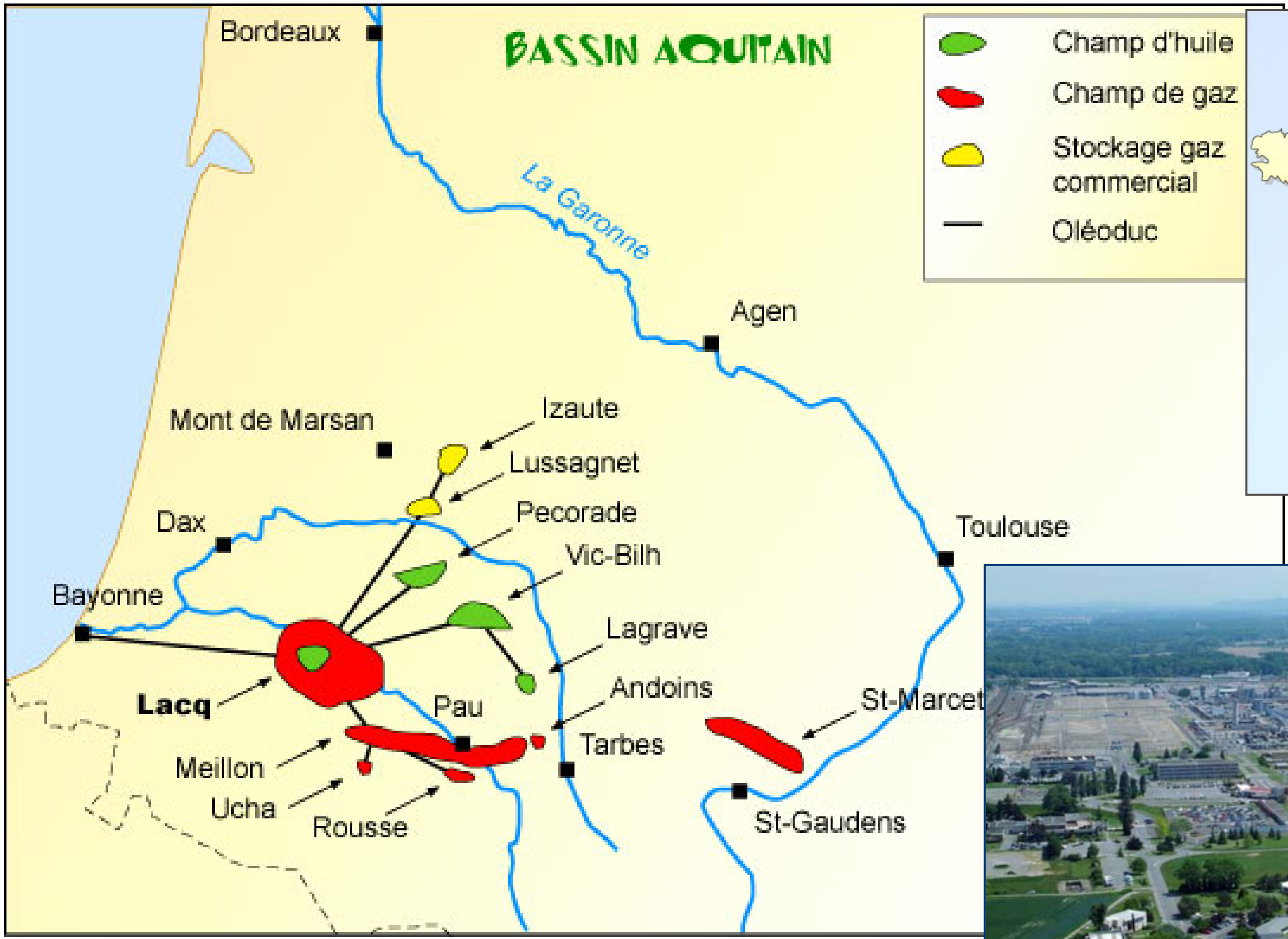
TOTAL

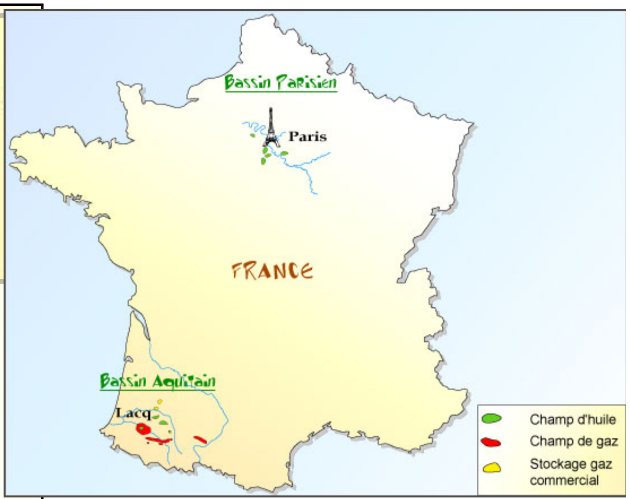
Oxy-combustion goals



- **Estimated CO2 capture and injection cost (500MW – 800 t/h steam – Canada)**
  - Post combustion: 75 $/t CO2 avoided
  - Oxycombustion: 45 to 35 $/t CO2 avoided

Pilot location
Total Exploration & Production in France

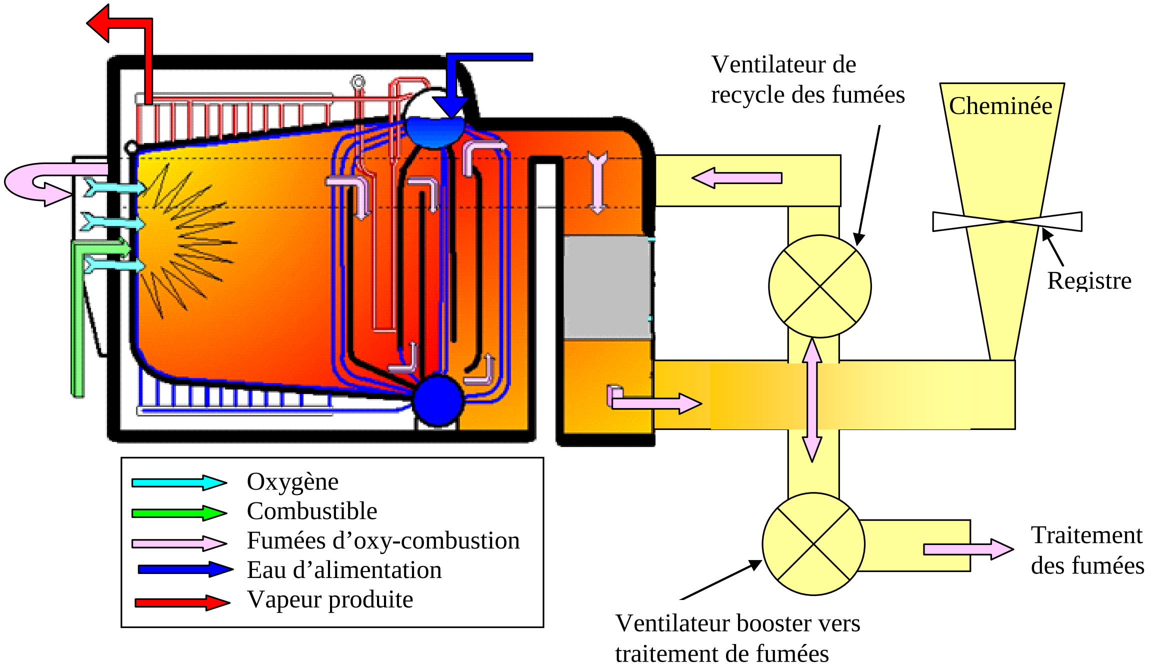




TOTAL

Boiler revamping

- Existing boiler revamping with CO_2 recycling
- 40 t/h of steam 60b/450°C (30MWth) to HP steam network



ALSTOM | AIR LIQUIDE

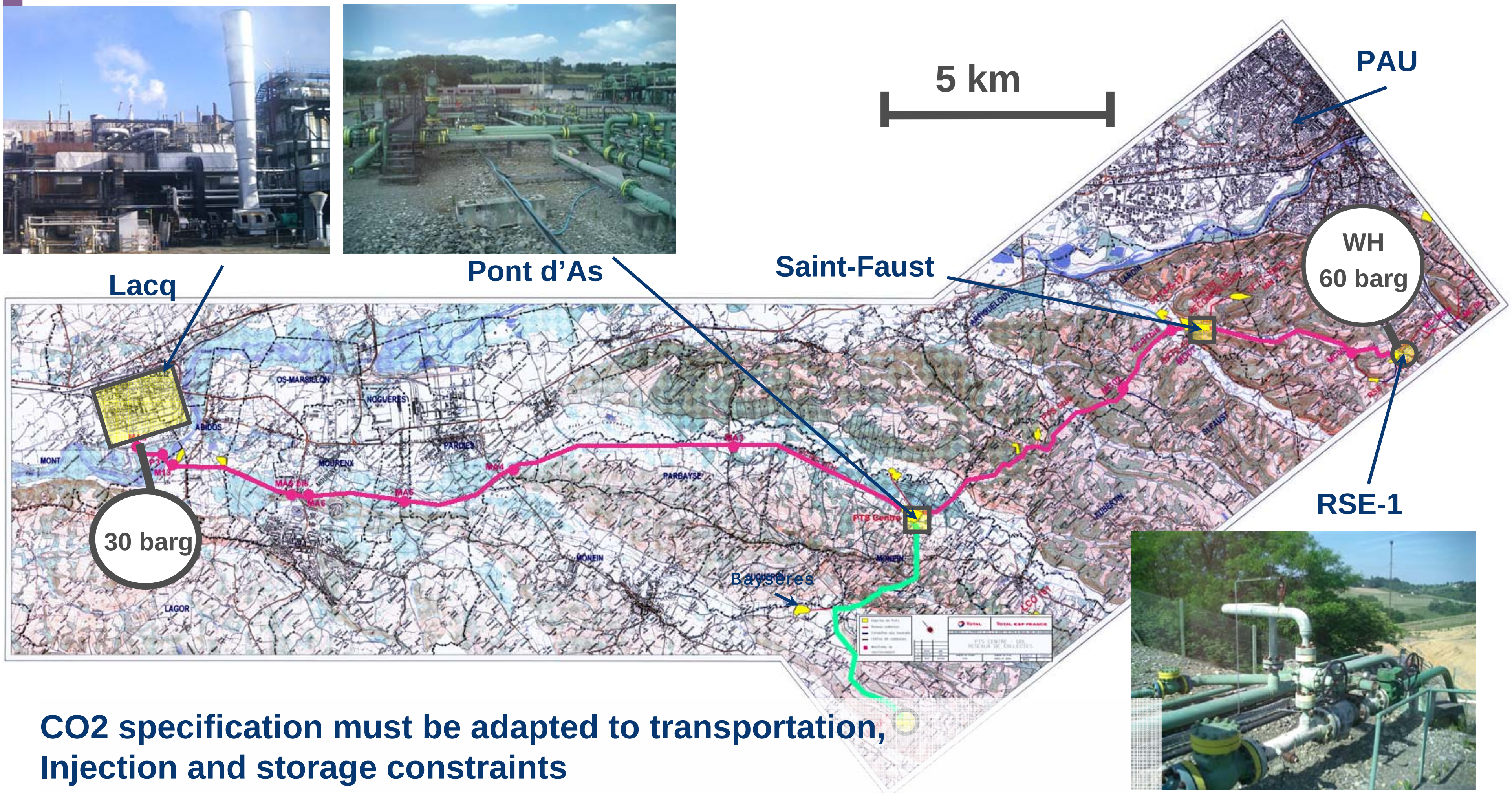
- ALSTOM in charge of boiler revamping study
- Air Liquide developping and providing oxyburners
- 240t/day oxygen required

Oxyburner development for Lacq pilot

AIR LIQUIDE
Industrial Partner

- **1MW prototype tested at Air Liquide Research and Technical Center (Jouy en Josas)**
- **4 x 8 MW dual fuel burners to be installed in existing slots**

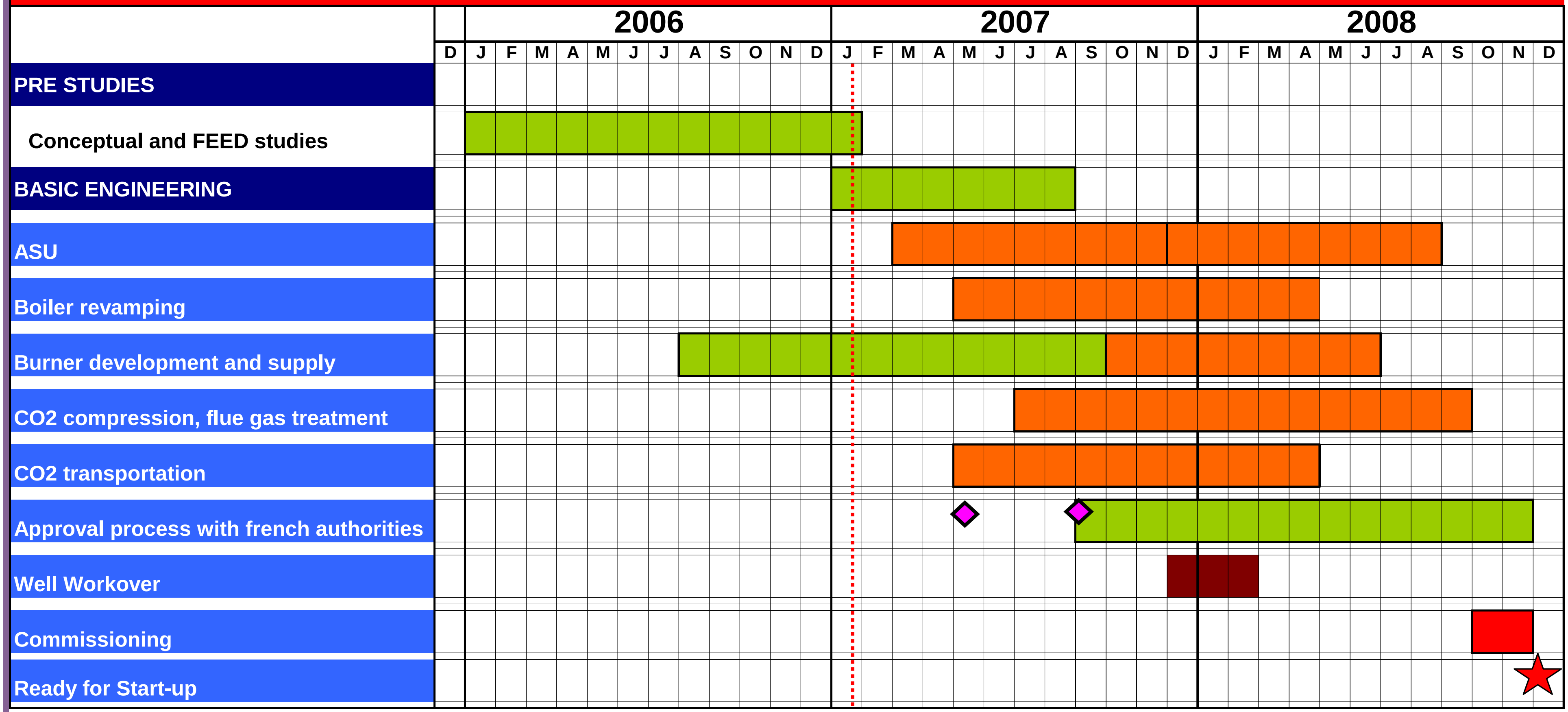
Transportation and injection into a gas depleted reservoir



CO2 specification must be adapted to transportation, Injection and storage constraints

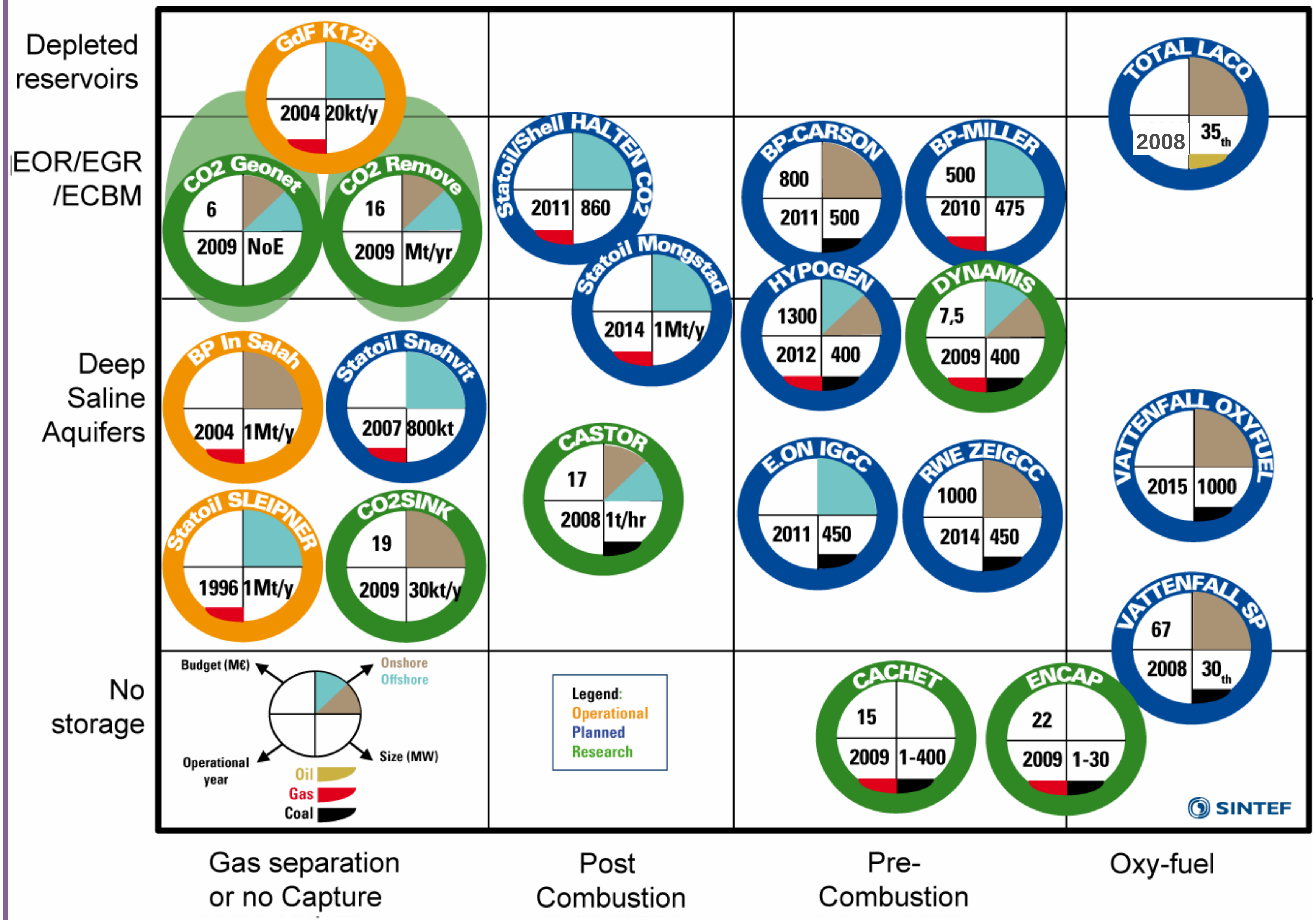
- * sub critical transportation and injection the first years
- * CS pipeline material and winter conditions
- * downgraded operation
- * impact studies for transportation (Phase 2 SOx content)
- * reservoir type (carbonates, aquifer, fluids in place, injectivity ...)

LACQ - OXYCOMBUSTION and CO_2 STORAGE PILOT



Rev.No : 2a **Date 30/11/06** **Page : 1 / 1**

Carbon Capture and Storage initiatives must cover the matrix



The Saskatchewan Advantage

SaskPower Clean Coal Project Update

2007 Jan 26

IEA International Oxy-Combustion Network
Windsor, CT

Bob Stobbs, P.Eng.
SaskPower

Presentation Overview

- Opportunity
- Economics
- Sustainability
- Technology
- Plan Forward

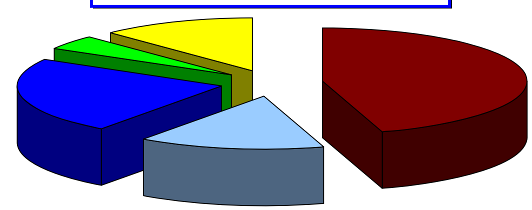
Power Generating Facilities in Saskatchewan
December 2006

CAPACITY	NET MW
Sask*Power* Facilities:	
Coal	1,653
Hydro	853
Natural Gas	538
Wind (Cypress)	11
Sask*Power* Total	**3,055**
Independent Power Producers (IPP):	
Meridian (Natural Gas)	211
Cory (Natural Gas)	228
SunBridge (Wind)	11
IPP Subtotal	**450**
Sask*Power* - Total Capacity Available December 31, 2005	**3,505**
Centennial Wind Facility - completed Spring 2006	150
Total Capacity Available 2006	**3,655**

Number of Customers	444,000

Transmission Interconnection Capacity	600 MW
With:	
Manitoba Hydro	300 MW
Basin Electric (North Dakota)	150 MW
Alberta (D.C.converter)	150 MW

2006 Generation Capacity Available (net MW)



- Coal 45%
- Natural Gas 15%
- Hydro 23%
- Wind 5%
- Purchase Power 12%

Record System Peak Load: 2,960 MW (net) Nov 29, 2006

The Saskatchewan Advantage

Capacity Need

Legislated Requirement to Serve

Fuel Availability

Environmental Stewardship

Kyoto Protocol

Proven Sequestration Effectiveness

Value for CO_2

Fed/Prov Cooperation (MOU)

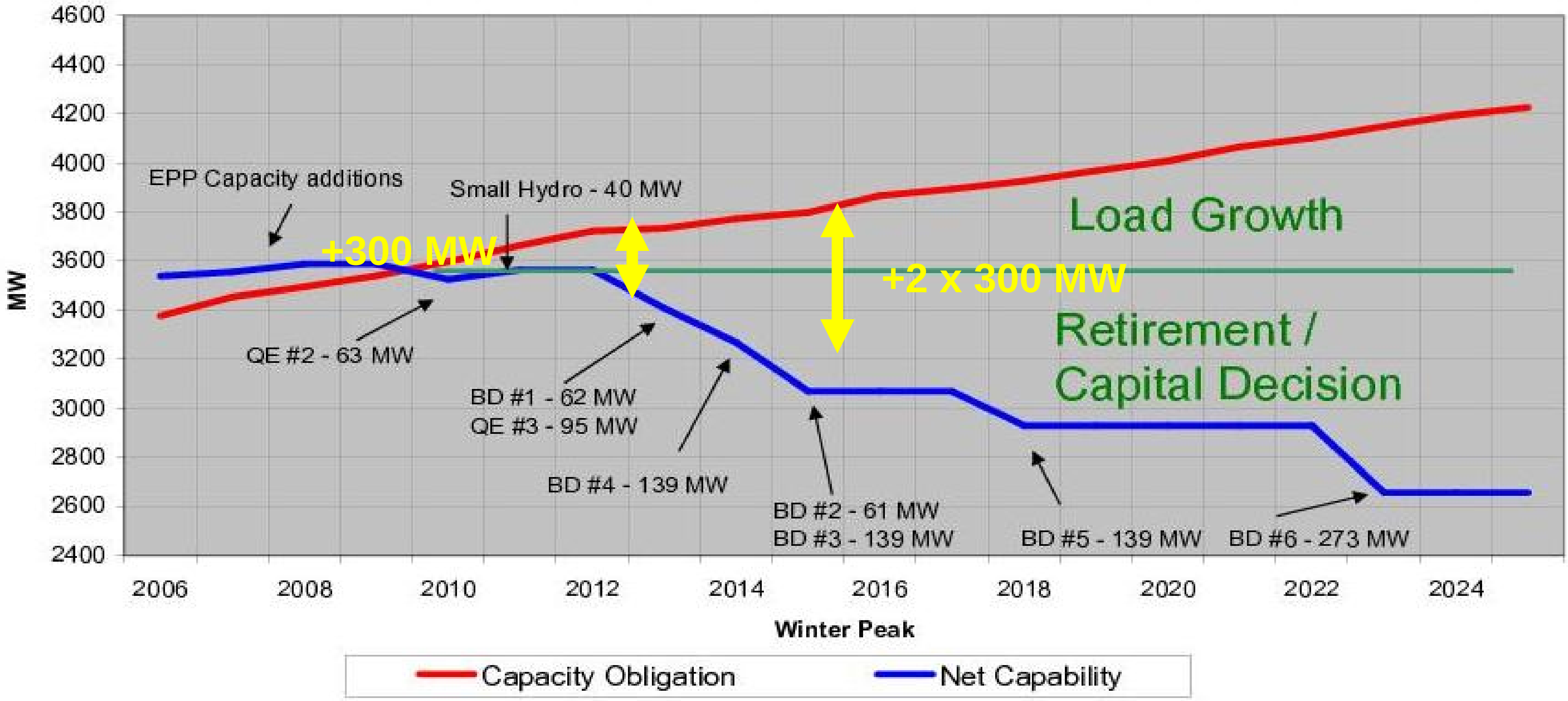
Work of the PTRC, SRC, ITC

Technical/Financial Capacity

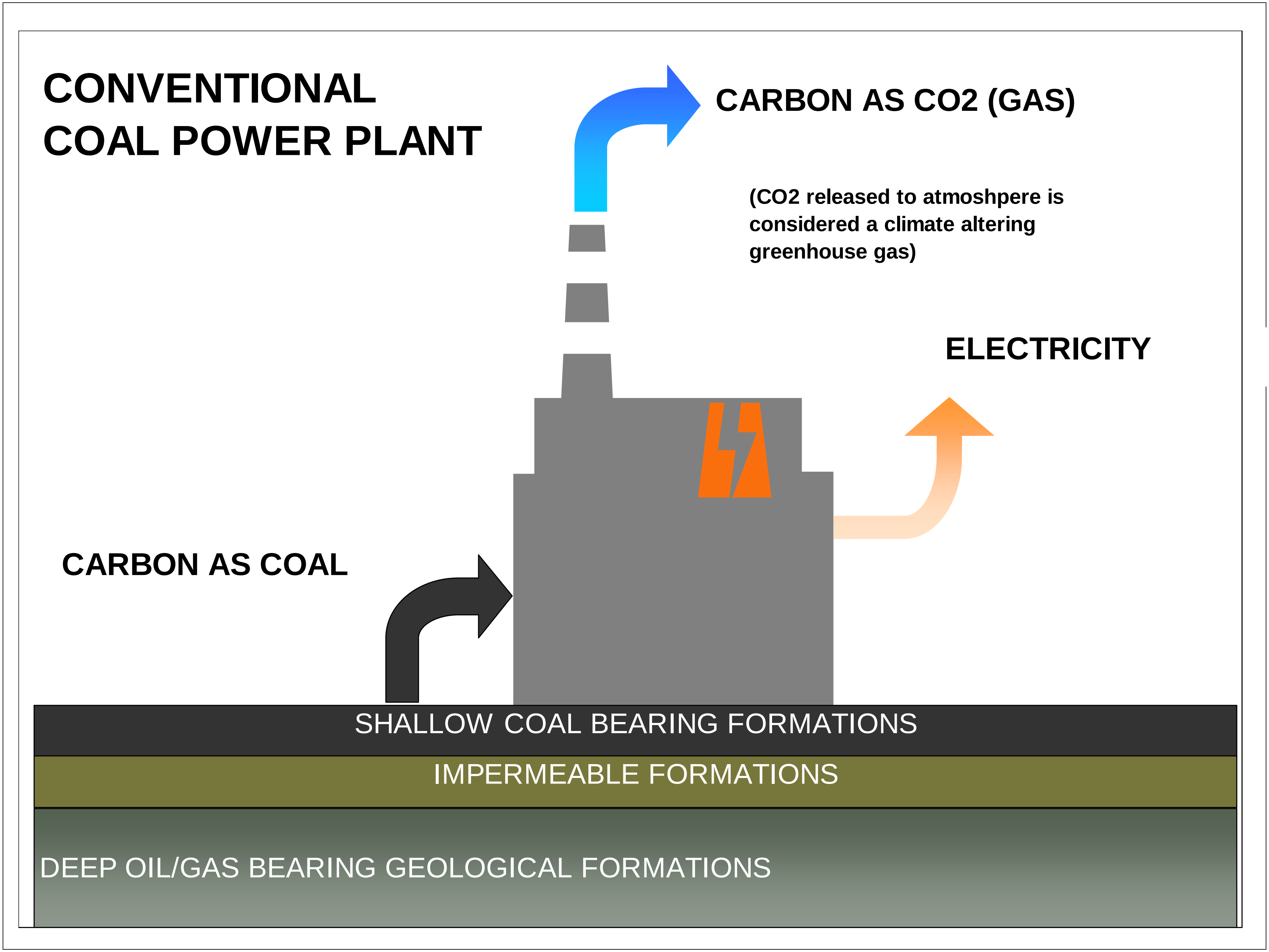
300 MW (near) Zero Emissions Pulverized Coal Plant in 2011?

SaskPower Capacity Position

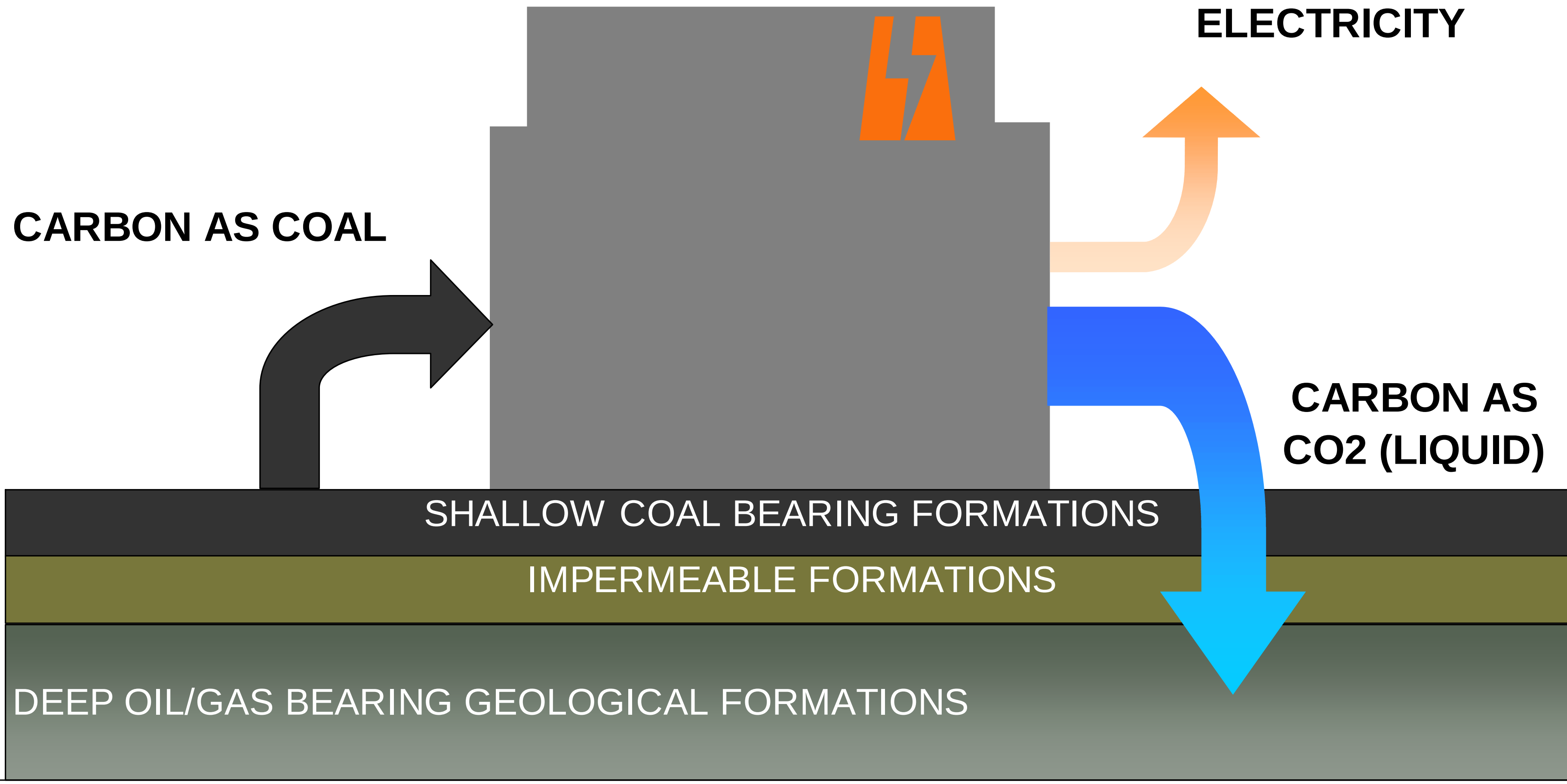
Base



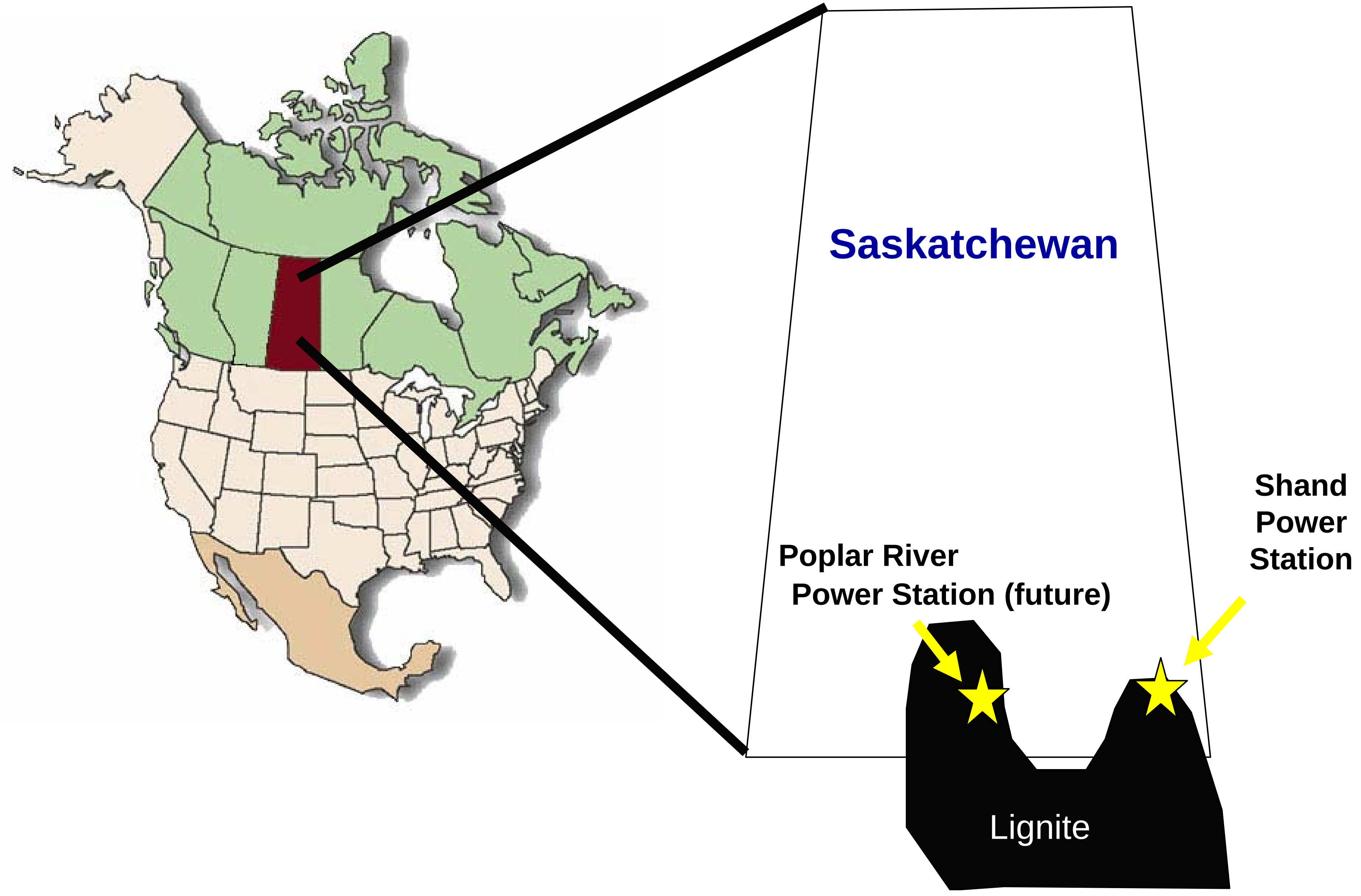
Peaking plants are assumed to be replaced in-kind.

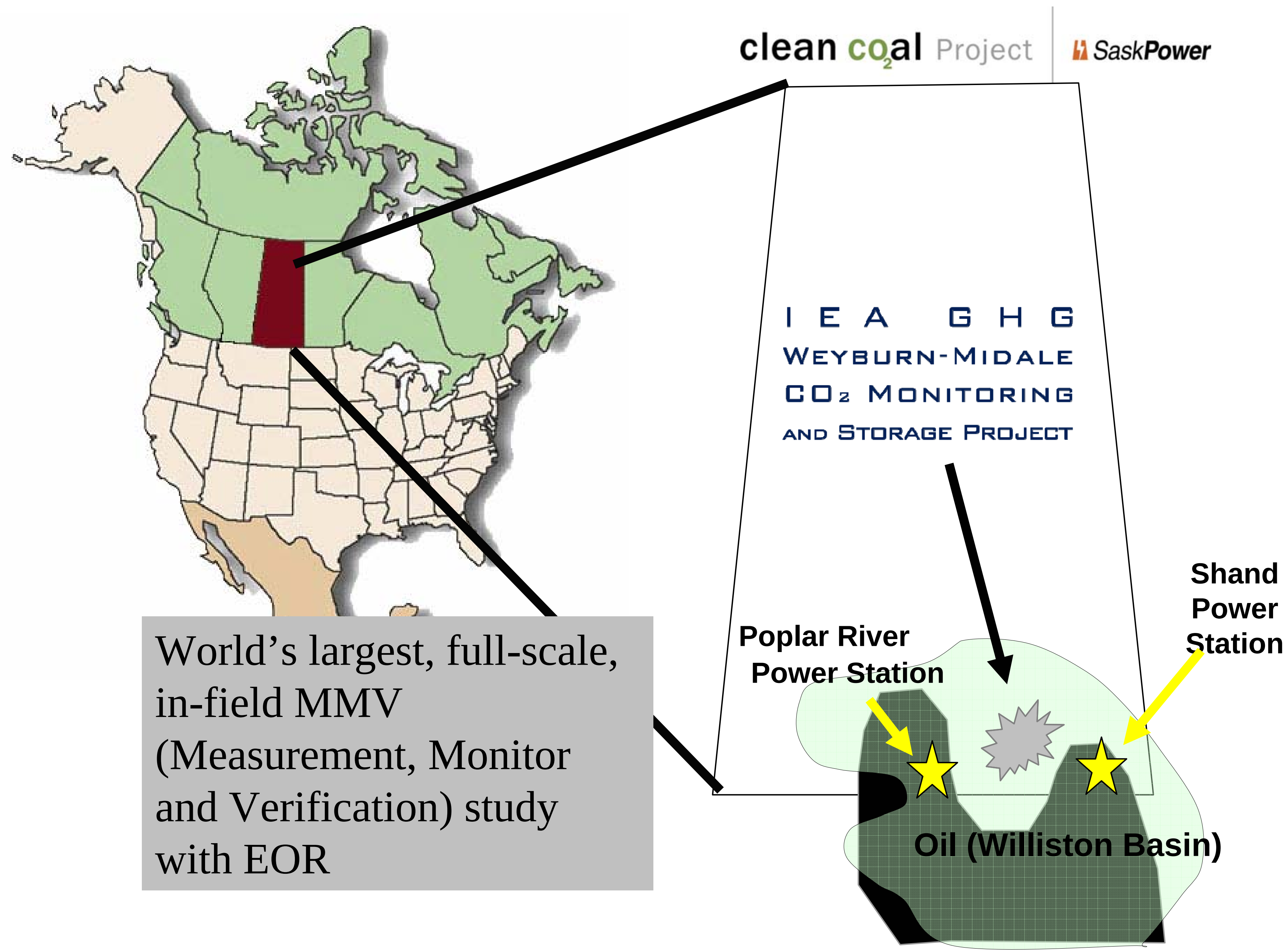

CONVENTIONAL
COAL POWER PLANT
CARBON AS CO2 (GAS)
(CO2 released to atmoshpere is
considered a climate altering
greenhouse gas)
ELECTRICITY
CARBON AS COAL
SHALLOW COAL BEARING FORMATIONS
IMPERMEABLE FORMATIONS
DEEP OIL/GAS BEARING GEOLOGICAL FORMATIONS

SaskPower's CLEAN COAL POWER PLANT



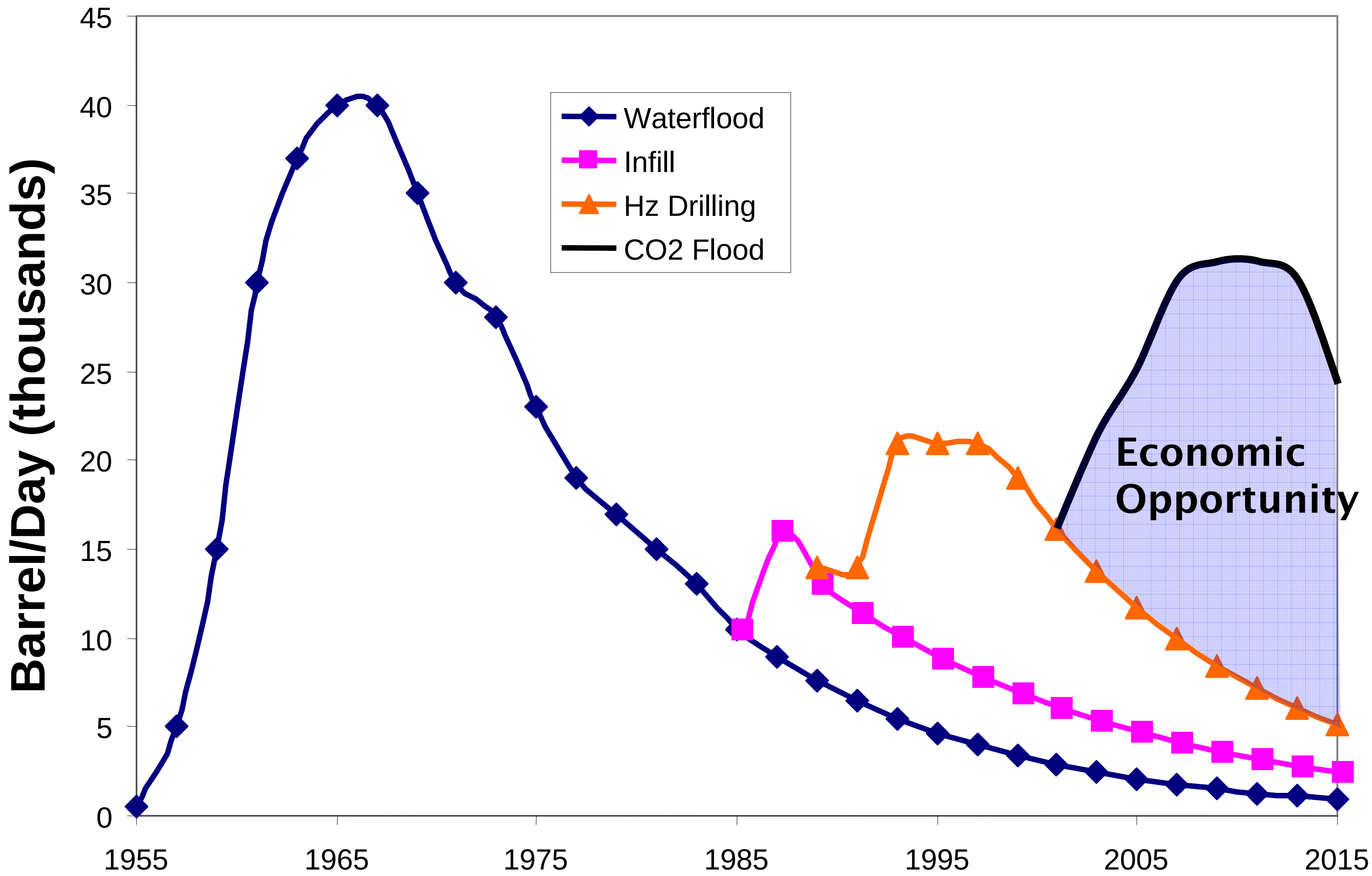
clean co2al Project | SaskPower




clean co2al Project
SaskPower
IEA GHG
WEYBURN-MIDALE
CO2 MONITORING
AND STORAGE PROJECT
Poplar River
Power Station
Shand
Power
Station
Oil (Williston Basin)
World's largest, full-scale, in-field MMV (Measurement, Monitor and Verification) study with EOR

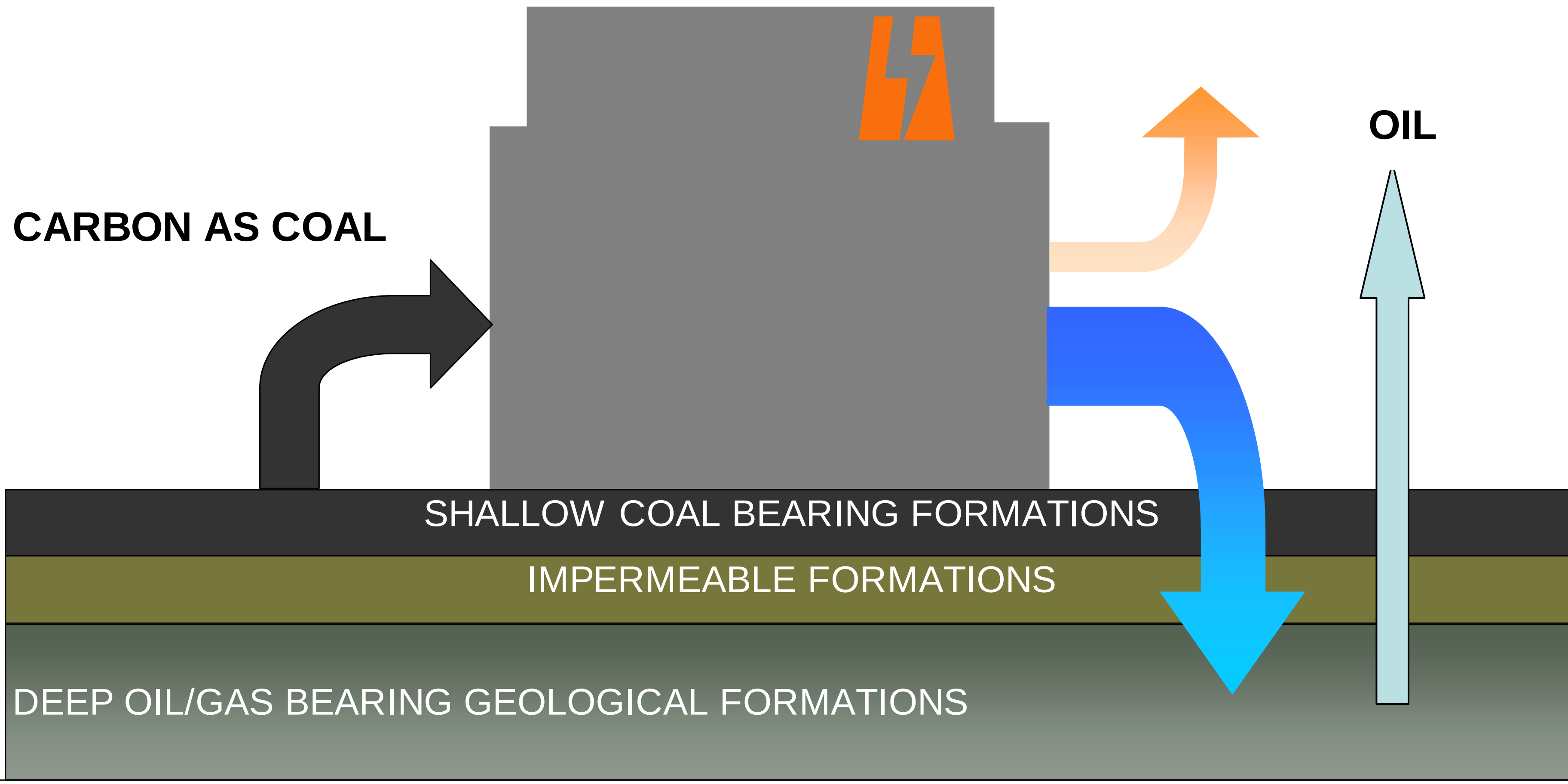
clean co2al Project | SaskPower

Weyburn Pool Production History



SaskPower's CLEAN COAL POWER PLANT

With Cogeneration of CO_2



Economics

Two Product Streams:

Electricity:

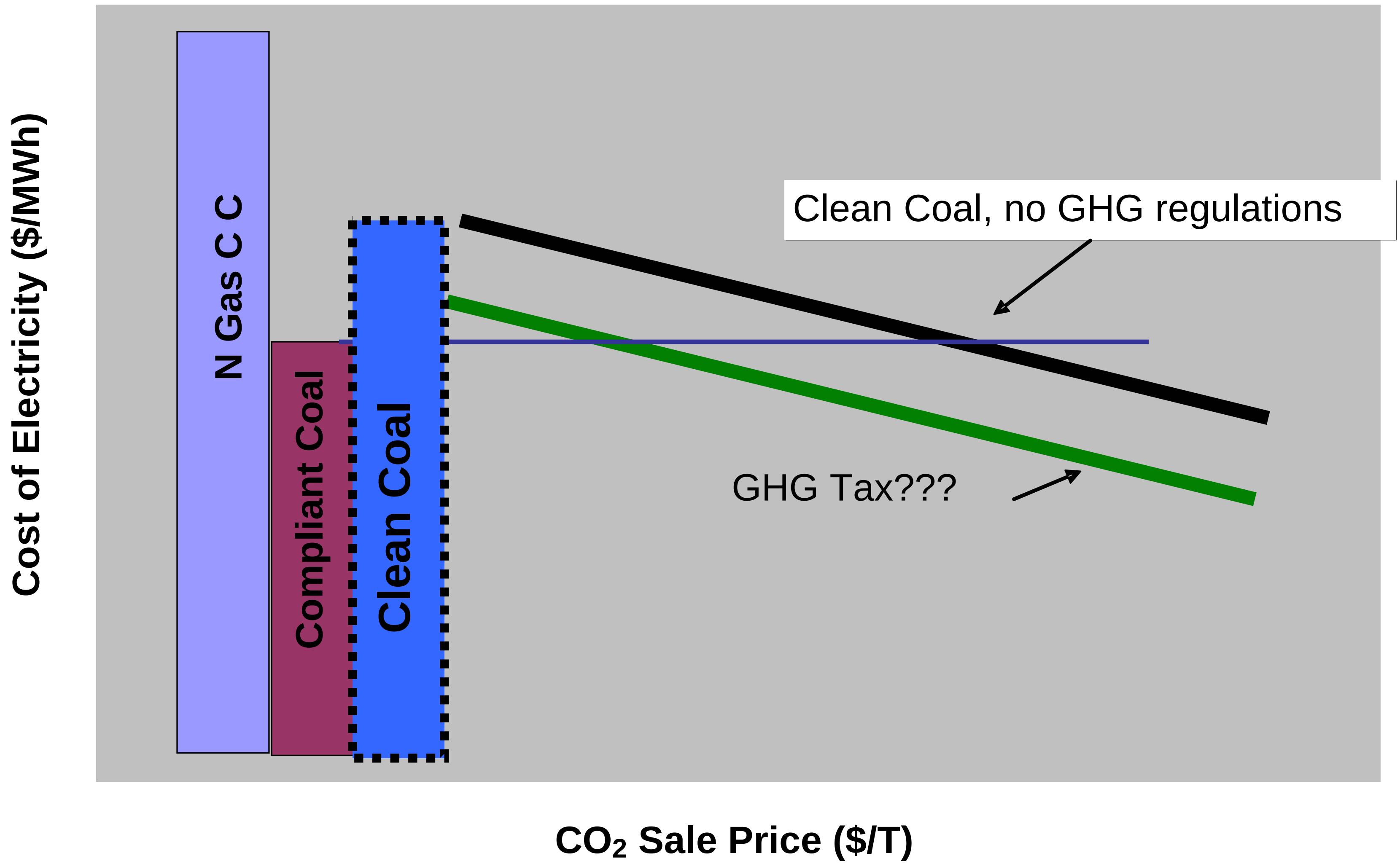
- Evaluated by internal procedures

CO_2 for Enhanced Oil Recovery:

- Evaluated by contracts in place as of June 2007

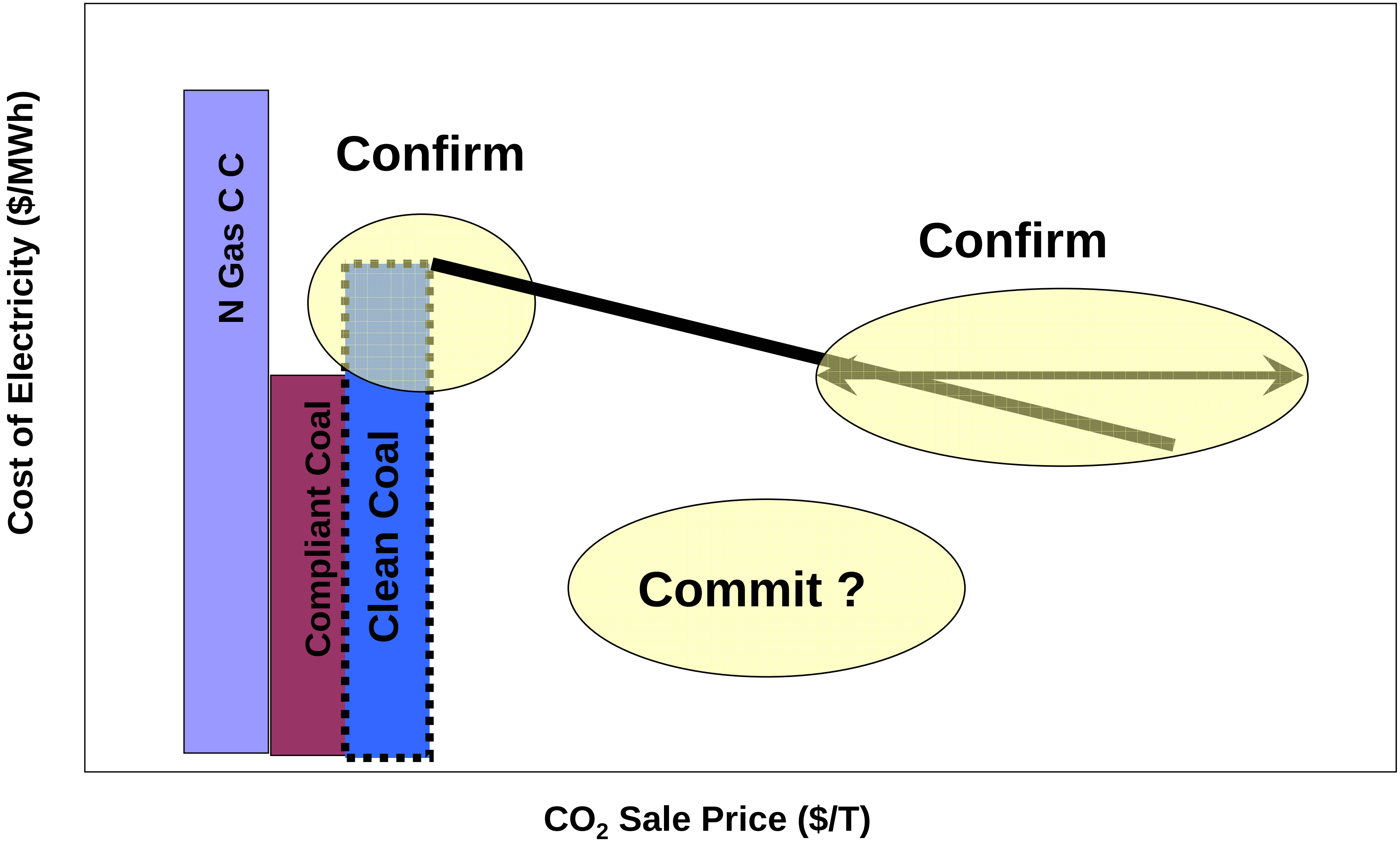
clean co2al Project | SaskPower

Preliminary Cost Comparison 300 MW Base Load



clean co2al Project | SaskPower

Precommittment Engineering Priority

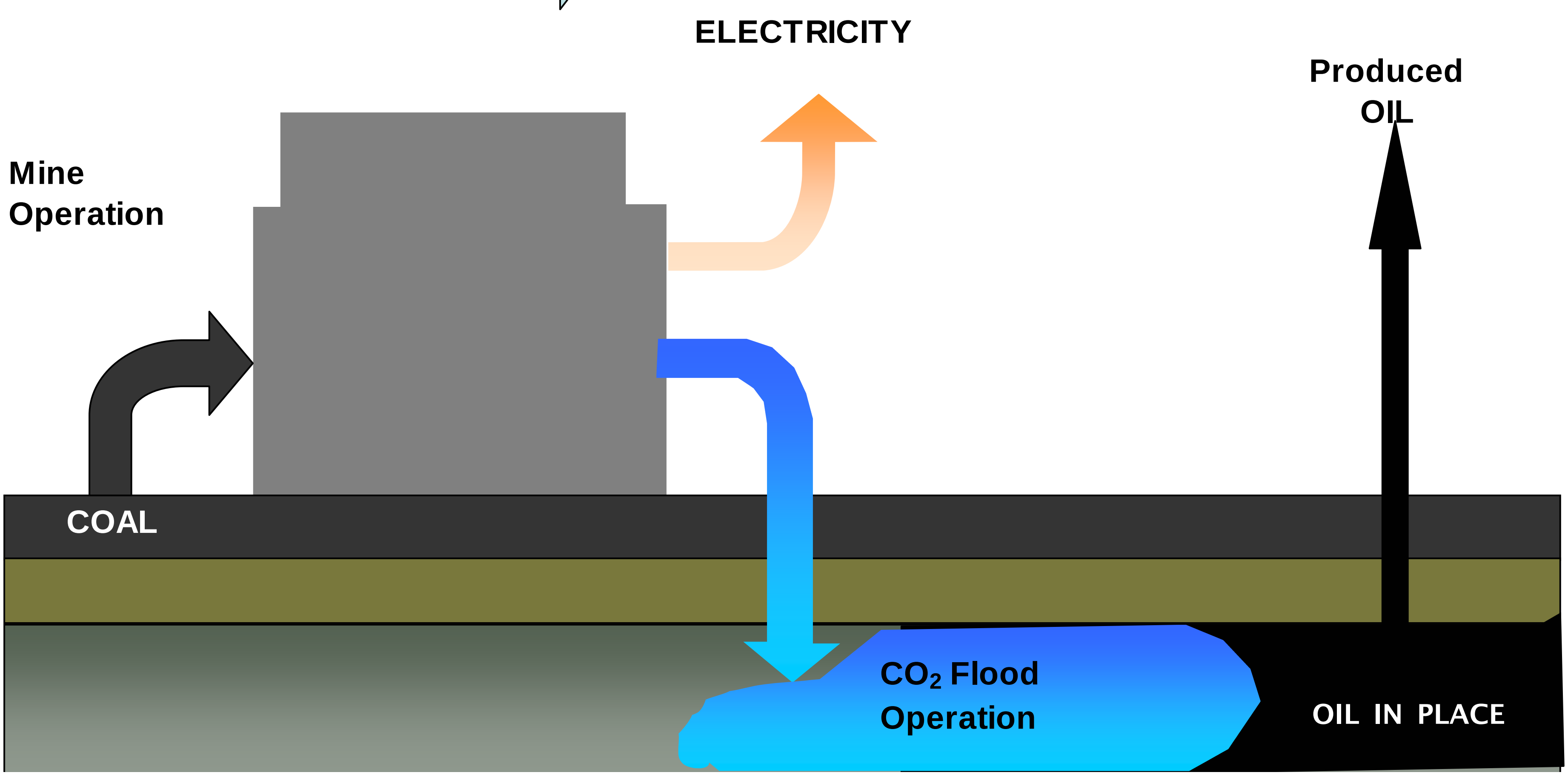


Sustainability and Environmental Performance

clean co2al Project | SaskPower

Overall COAL to OIL Process

1 Tonne Coal → Produces → 0.8 MWh + 2 to 10 barrels Oil



clean co2al Project | SaskPower

ENERGY BALANCE

1 Tonne Coal → Produces → **0.8 MWh + 2 to 10 barrels Oil**

<u>Energy Out:</u>

0.8 MWh =	+ 3			GJ	(electrical)
2 to 10 bbl =	+ 12	to	60	GJ	(fossil)

<u>Energy In:</u>

1 Tonne =	- 13	GJ	(fossil)

Net Energy Produced: + 2 to 50 GJ (elect & fossil)

Net Emissions Impact

Near Zero emissions electricity plus:

1 Barrel Weyburn Crude: Equivalent to 1.0 GHG unit

Offsets →

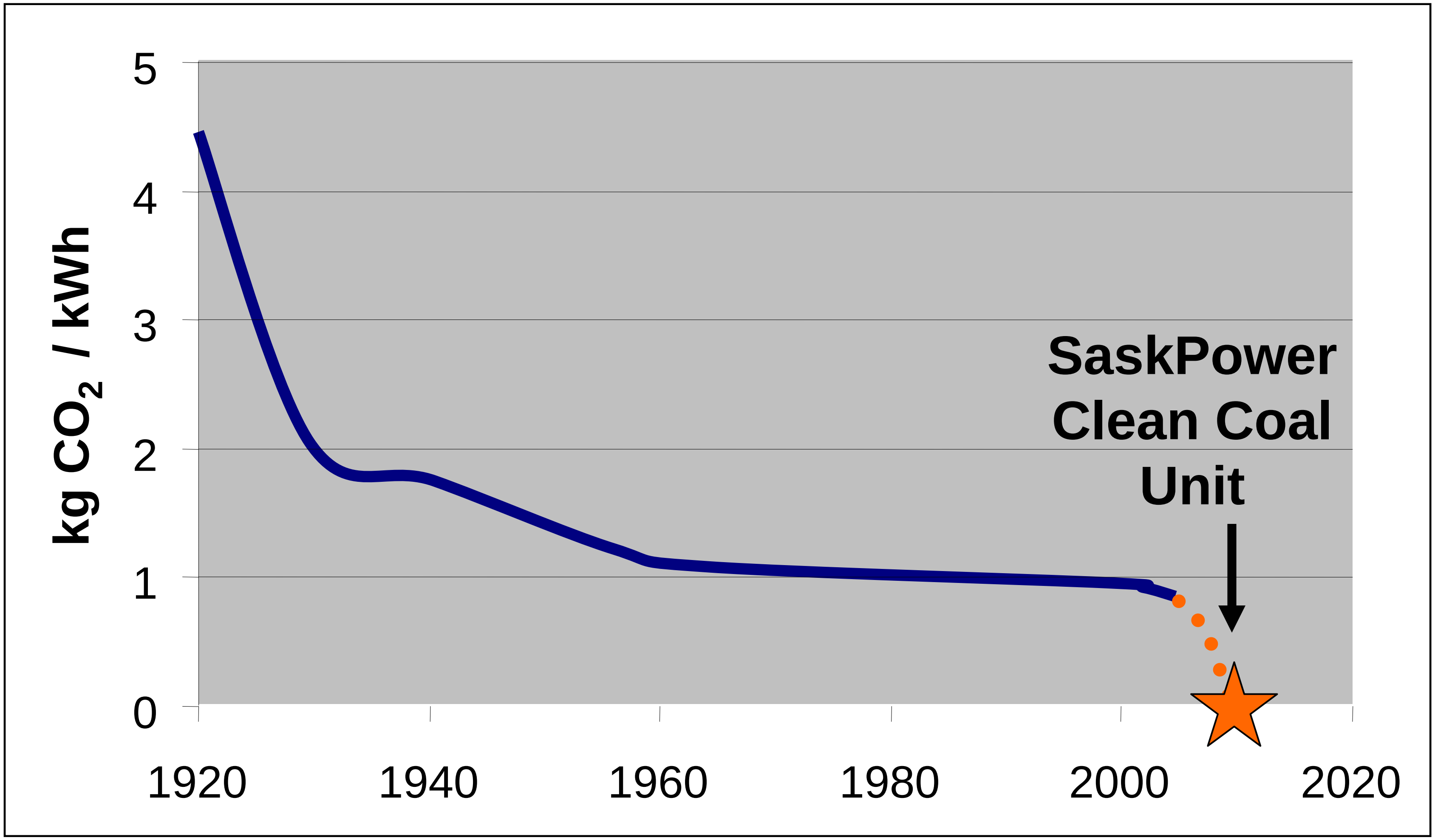
1.3 to 1.4 GHG equivalents Saudi oil

or

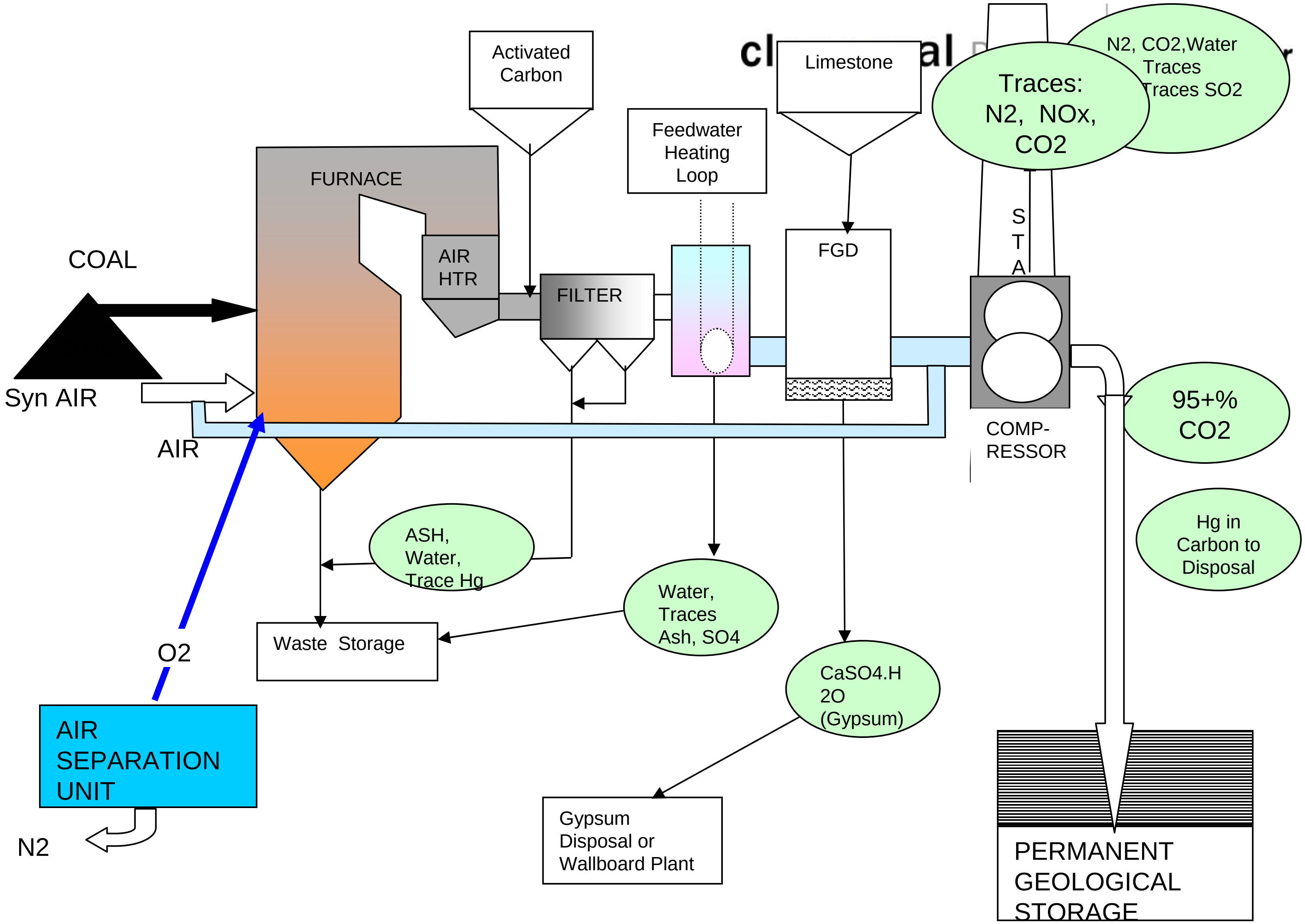
1.9 GHG equivalents Alberta Oil Sands

clean co2al Project | SaskPower

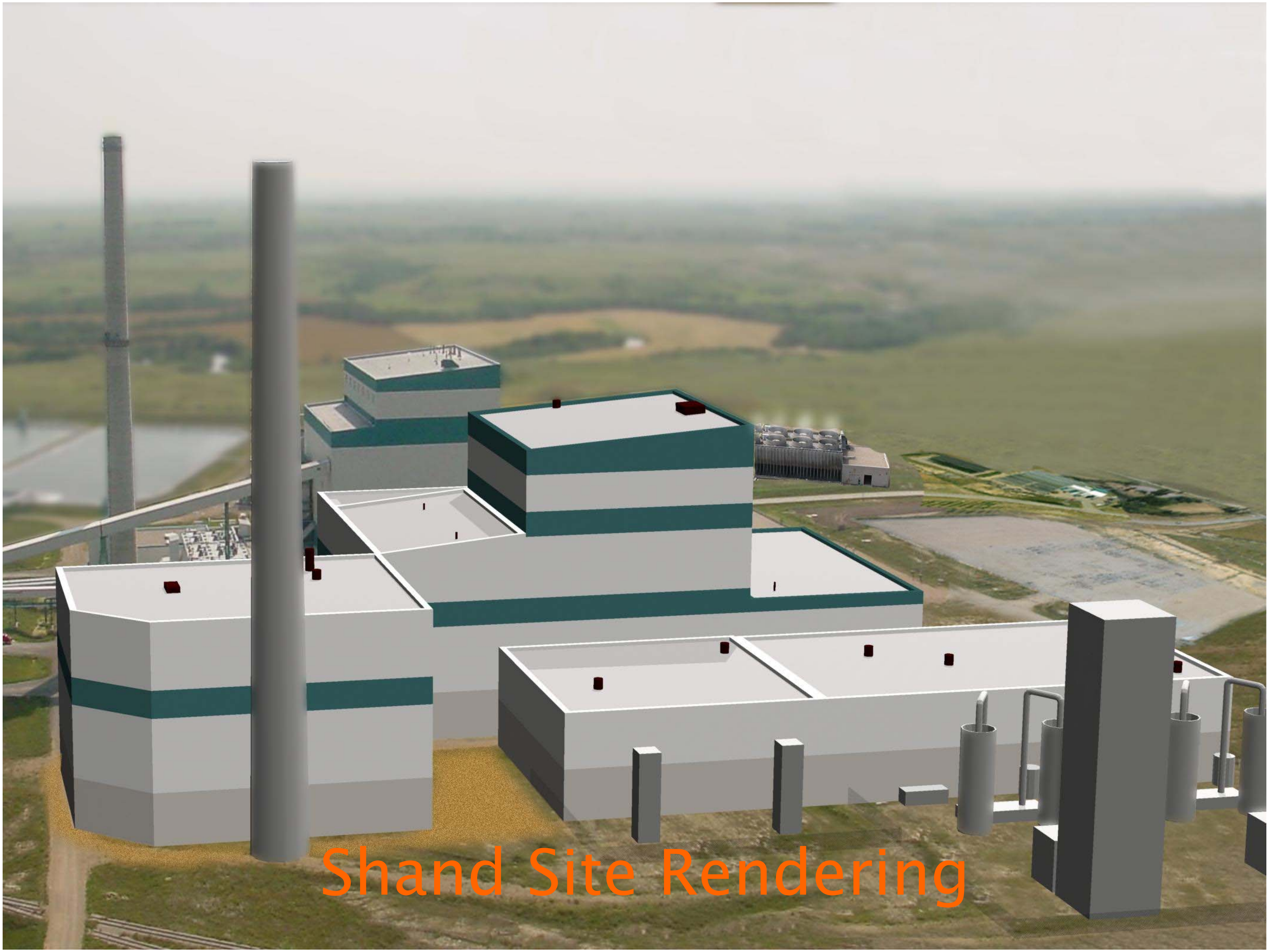
100 Years of Progress in Reducing Emissions Intensity



Technology



SaskPower Oxyfuel Process


Shand Site Rendering

clean CO_2al Project | SaskPower

Contract Strategy

- Synthetic Air Boiler – Babcock & Wilcox
- Air Separation Unit – Air Liquide
- Compression & Purification Unit – Air Liquide
- Steam Turbine Generator-Marubeni/Hitachi
- Owner’s Engineer – Neill & Gunter
- Balance of Plant - TBA

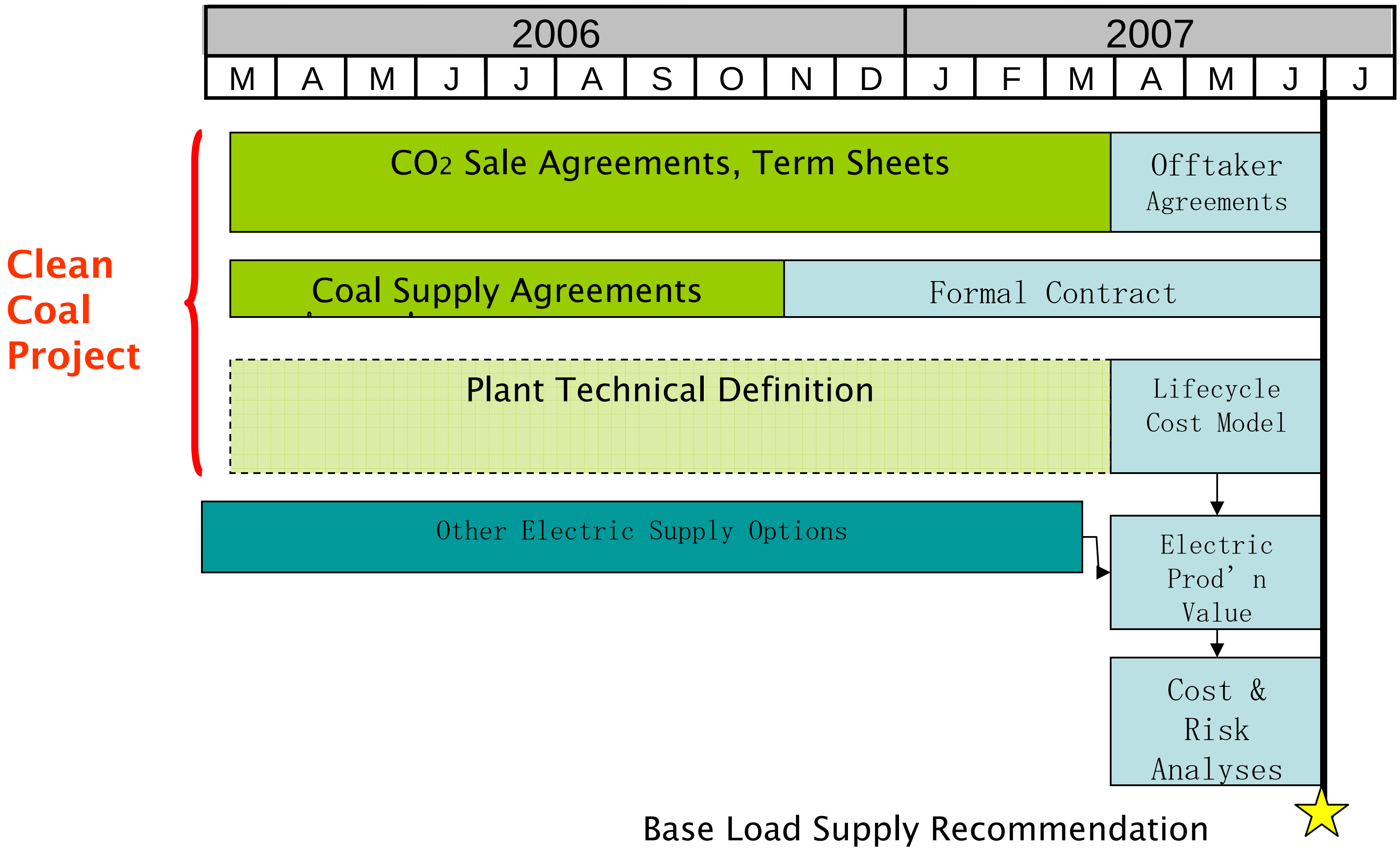
Project Proposal

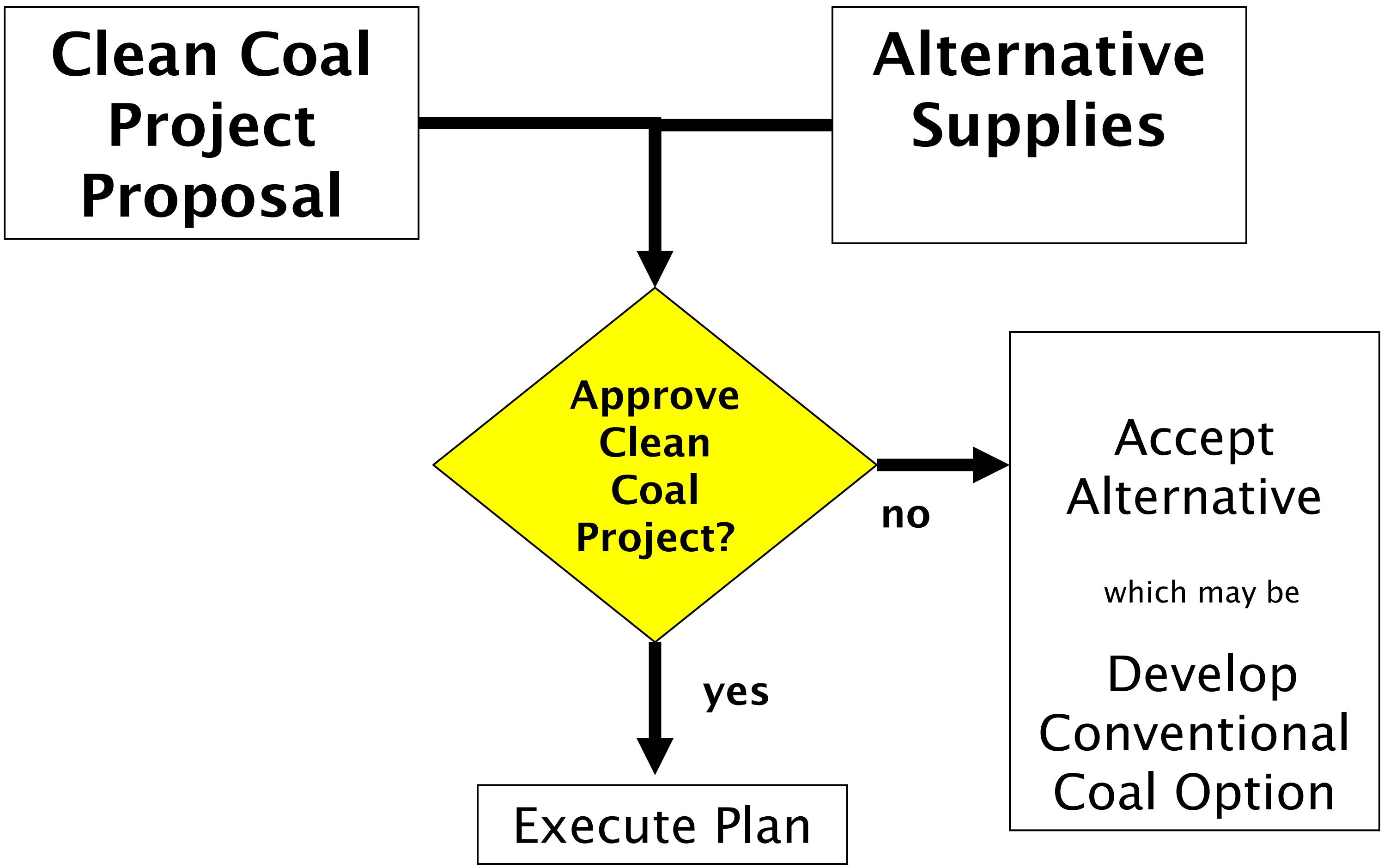
- The SaskPower Clean Coal Project Proposal (end June 2007) will include:
  - Business Case Analyses addressing cost, risk and revenue expectations
  - Provisional Equipment and Construction Contracts for immediate acceptance
  - Provisional CO_2 sales agreements for immediate acceptance
  - Project Execution Plan

Path Forward

clean co2al Project | SaskPower

SaskPower's Supply Decision




Clean Coal Project Proposal
Alternative Supplies
Approve Clean Coal Project?
no
Accept Alternative
which may be
Develop Conventional Coal Option
yes
Execute Plan

The Saskatchewan Opportunity

300 MW (near) Zero Emissions Pulverized Coal Plant in 2011?

→

Environmentally and Economically Sustainable Electricity Supply

Enhanced Oil Production

On-going and Enhanced Coal Royalties

Leading Edge Clean Coal Technologies to a Huge World Market

International Clean Coal Engineering & Technology Center

Expansion of In-Province Manufacturing Commitment

Economic Spin-offs from Project Construction


QUESTIONS?

Callide Oxyfuel Project Status

Presented by: Chris Spero
Oxyfuel Project Manager / Manager Engineering Technology
CS Energy

IEAGHG International Oxy-Combustion Network
Windsor, CT, USA
25 & 26 January 2007

cs energy

CCSD

Acknowledgement

Callide Partners:

CS Energy Ltd

Xstrata Coal (representing Australian Coal Association)

Schlumberger

IHI

JPower

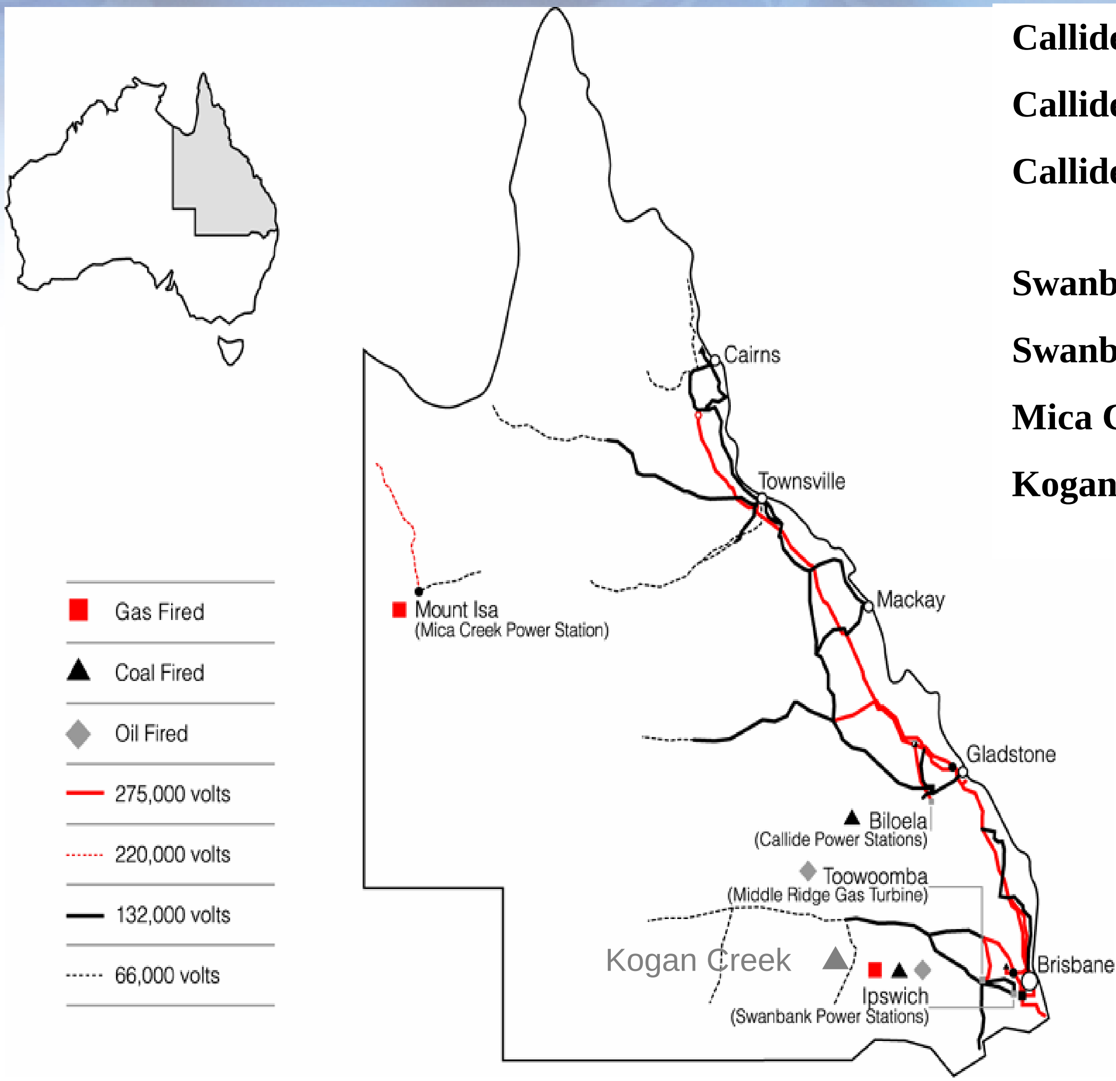
JCoal

Supporting Partners:

CRC for Coal in Sustainable Development (CCSD)

CRC for Greenhouse Gas Technologies (CO2CRC)

CS Energy

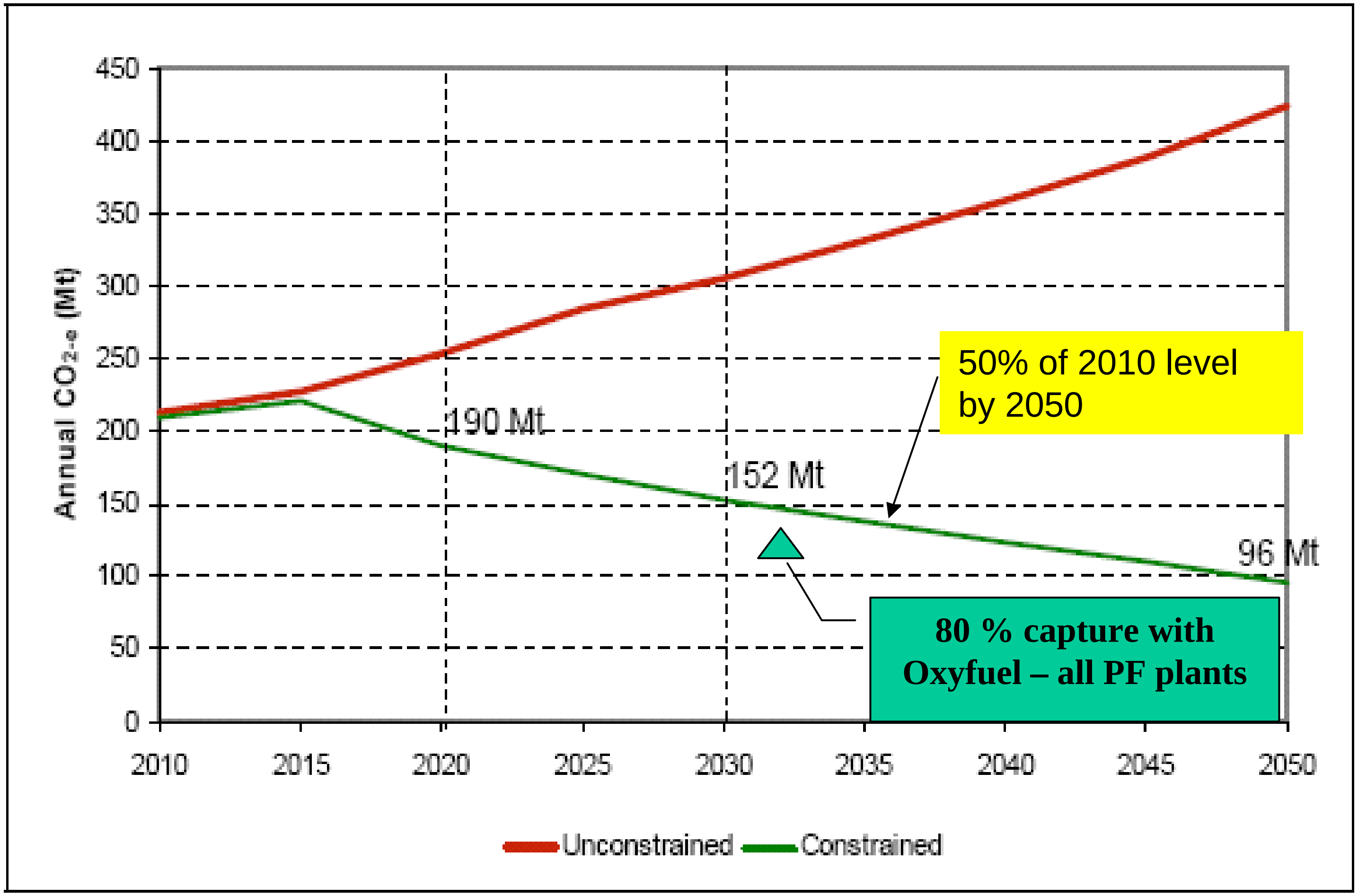


Callide A:	**4 x 30 MWe (PF)**
Callide B:	**2 x 350 MWe (PF)**
Callide C:	**2 x 460 MW (PF)** **Joint Venture (50%)**
Swanbank B:	**4 x 120 MW (PF)**
Swanbank E:	**1 x 385 MW (CCGT)**
Mica Creek:	**327 MW (Gas & CCGT)**
Kogan Creek:	**1 x 750 MWe (PF)** **(under construction)**

cs energy

CCSD

CO2 Forecast - Australia



cs energy

CCSD

Project achievements to date

Date	Milestone
Sep. 04	Feasibility study MOU signed ($1.3 million cash + in-kind)
Sep - Dec. 05	Pilot-scale tests conducted in Japan (addition $350,000 funding obtained)
Mar. 06	Demonstration Project MOU signed Low Emission Technology Demonstration Fund Application submitted
Jul. 06	Feasibility study completed
Oct. 06	• Funding announced by Commonwealth Government ($50 million) • Callide plant condition assessment completed (CBH, Siemens, IHI, Auspower, Energen)
Nov. 06	Preliminary design and hazard review completed (CS Energy, IHI, Gas Plant supplier)

cs energy

CCSD

Plant condition assessment & design review outcomes

Plant Condition:

- Plant is in better condition than expected (especially boiler walls, drums, rear pass, baghouse, switchgear, field devices & actuators)
- Some work required on cold side of airheater as expected, and control system upgrade

Design review:

- Design parameters largely agreed
- DR revealed some layout and access issues relating to Oxygen and CO2 plant

cs energy

CCSD

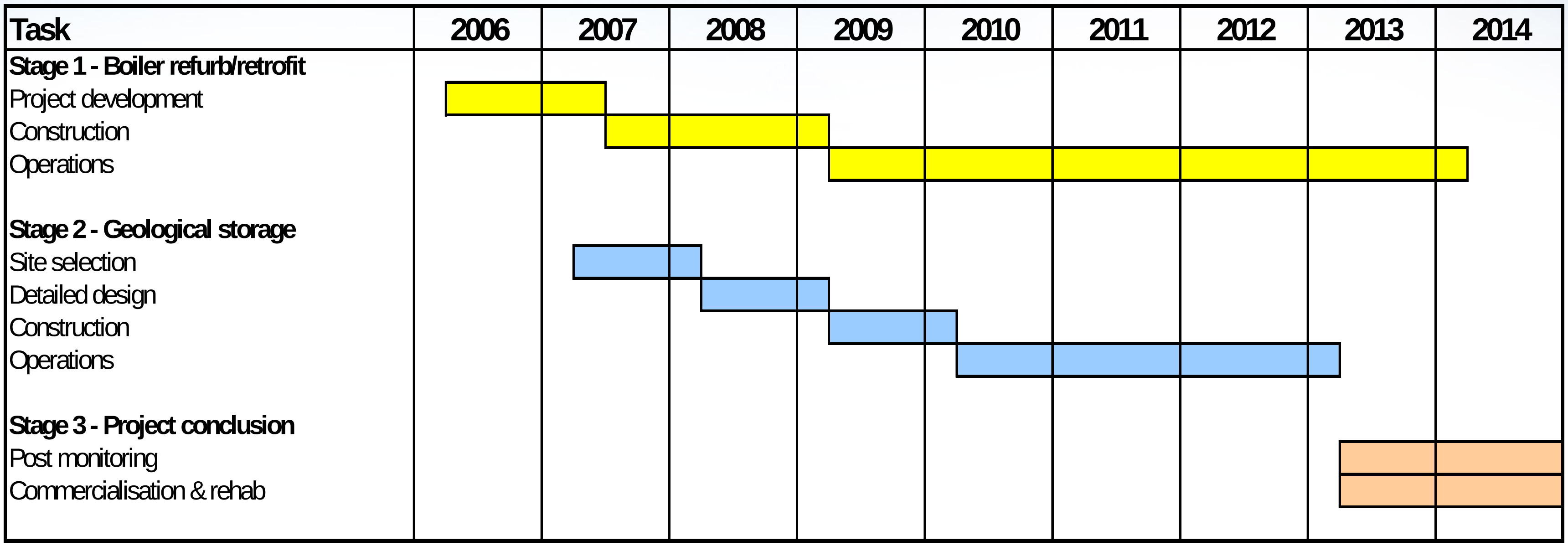
Milestones to financial closure

Milestone	Target
Publish feasibility study report	Feb. 07
Draft Commonwealth Funding Agreement and JV Agreement	Feb. 07
Finalize design & operating parameters report	Feb. 06
Geosequestration workshop	Mar. 07
Plant specifications – Oxygen plant – Boiler refurbishment (CBH) – Retrofit (IHI) – CO2 plant	Mar. 06
Finalize environmental assessment & re-licensing	May 07
Final business plan	May 07
EPC contracts, IJV & supporting agreements formed	Jun. 07
Financial close	Jun. 07

cs energy

CCSD

Callide oxyfuel project schedule



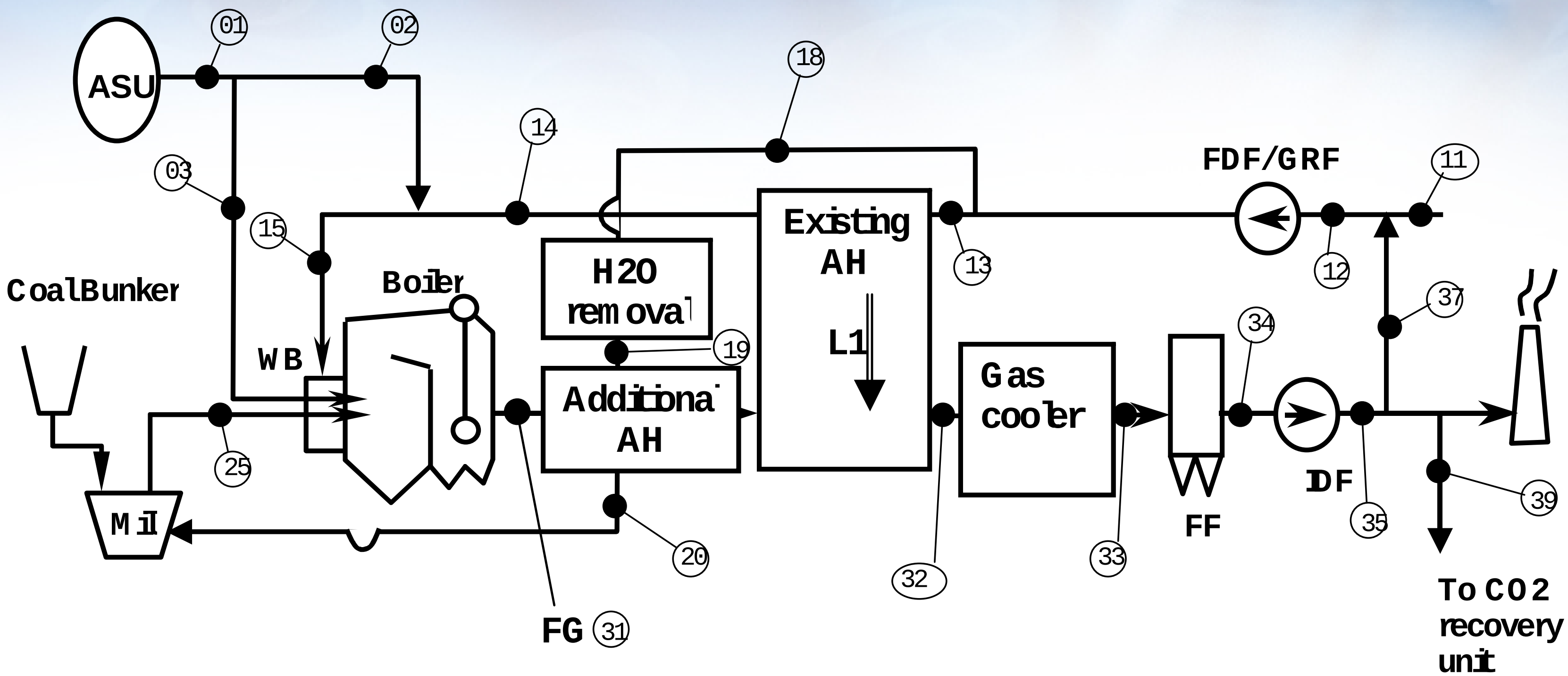
Project scope

- Nominal 660 tpd O2 supply (@ 98% purity)
- Overhaul and refurbishment of 1 x 30 MWe boiler/STG
  - Control system
  - Coal handling plant (mainly with respect to electrical safety)
  - Airheater (cold end) retubing
- Retrofit of boiler for oxy-combustion and flue gas recirculation
  - Modification to ductwork and new FD & ID fans
  - Gas cooler/Feedwater heater (at fabric filter inlet)
  - Additional gas airheater (on hot side of the existing airheater)
  - Gas dryer for flue gas feed to the mills
  - CO2 gas to Fabric Filter pulsing system and other gas seals
- Flue gas processing and CO2 capture (80 – 100 tpd)
- New control system & additional electrics
- 100 t on-site cold storage
- Road transport of up to 100 tpd CO2 (max)
- Geological storage (~ 100,000 t over 4 years)

cs energy

CCSD

Callide oxyfuel schematic



cs energy

CCSD

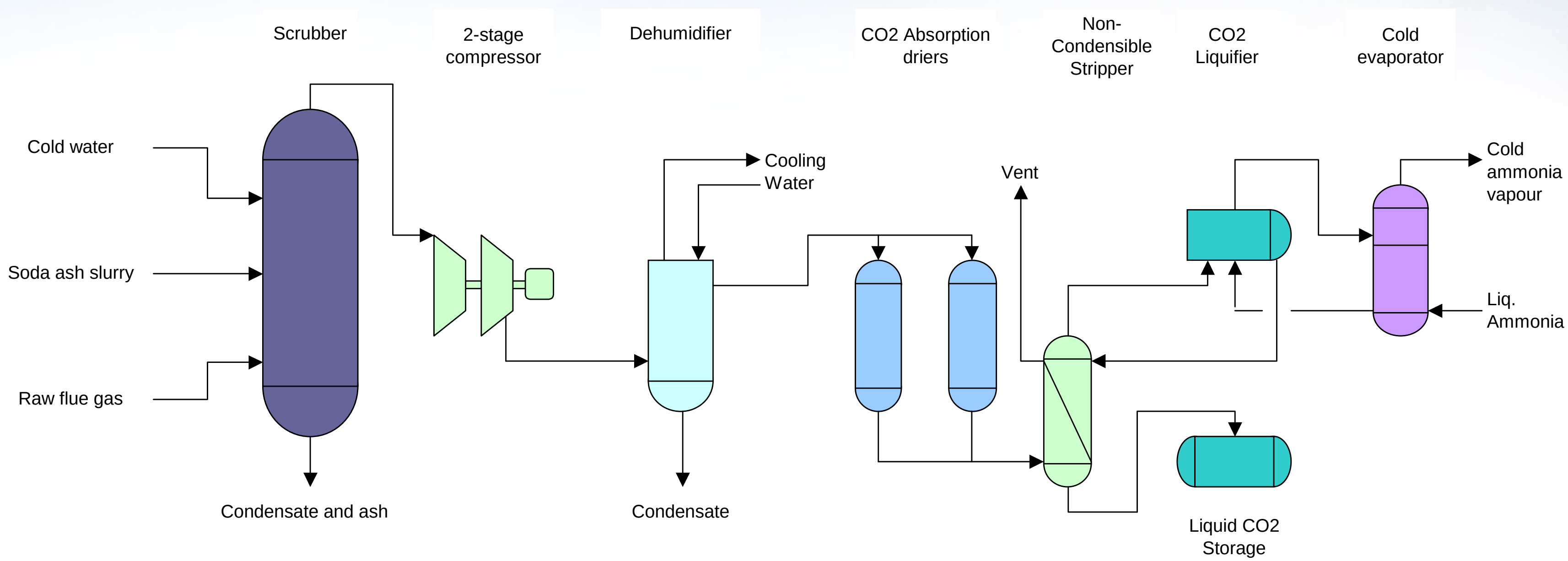
Callide burners

- 3 rows x 2 flare burners/unit
- 2 rows in-service for full load
- Coal flow: ~ 1.35 kg/s/burner
- Direct O2: ~ 0.5 kg/s
- Dry RFG: ~ 9.0 kg/s
- Windbox: ~ 7.4 kg/s O2 + 18.5 kg/s RFG
- Air registers can be rotated 180 ° clock-wise or anti-clockwise to adjust the length and shape of the flame
- Additional O2 can be introduced down the center of the burner for oxy-firing
- Overall combustion O2:
  - 27 vol. % into the furnace
  - 3 vol.% at rear pass exit

cs energy

CCSD

Flue gas/CO2 processing plant



Flue gas/CO2 processing plant

- Total flue gas: 45 kg/s
- CO2 process plant input: 15 kg flue gas/s

		Raw feed gas	**Product liquid**
Temp.	^{o}C	145	-18
Pressure	kPa(g)	0.1	2000
H_2O		18 - 20 %	< 0.02
O_2		3.0 - 4.5 %	< 0.3
N_2 (Ar)		12 - 16 %	< 2.0
CO_2	mol. %	60 - 70 %*	> 98
SO_2		0.08 - 0.12 %	
NOx (as NO_2)		0.015 - 0.025	< 0.1
Other			
Heavy metals (As, Be, Cd, Hg, V)	mg/kg liq. CO2		< 1
Other Trace Elements			< 10
CO_2 recovery	%		65 - 80

* Liquefaction limit is nominally 53 mol. % wet

cs energy

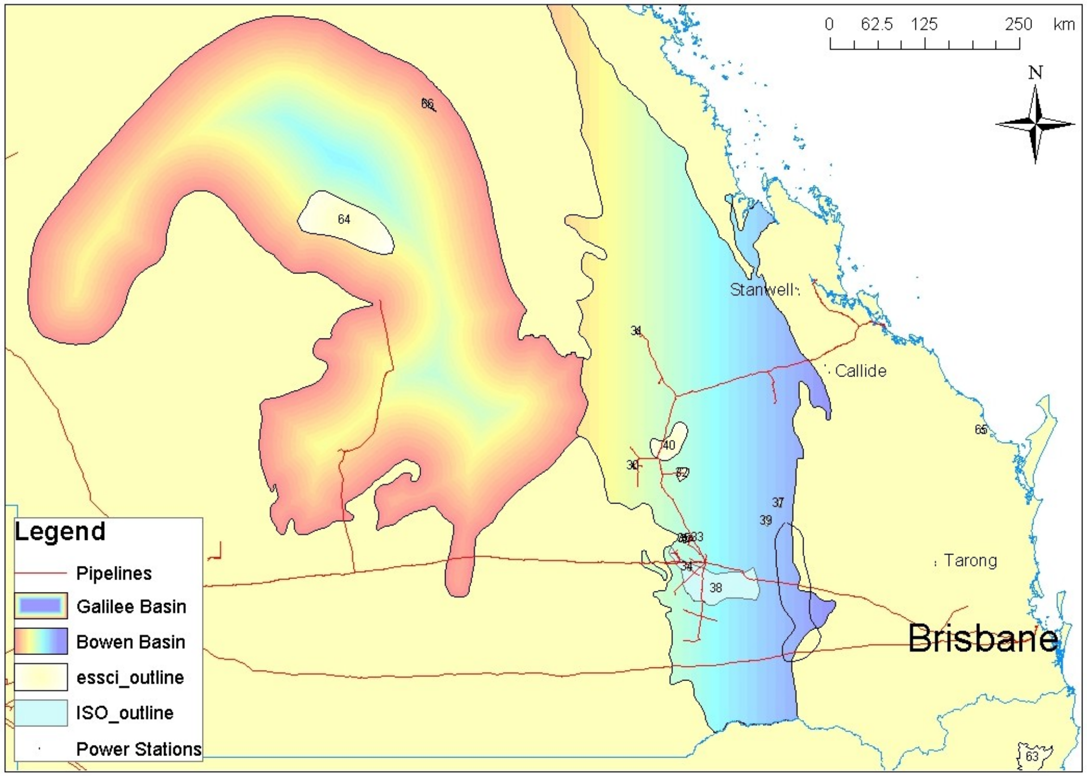
CCSD

CO2 storage

- Target is 25,000 – 30,000 t/yr for 4 years
- Storage options based on 'risked storage capacity' include:
  - Depleted gas fields 300 – 350 km from site by road in the Northern Denison Trough (~ 15 Mt CO2)
  - Enhanced Coal Bed Methane recovery from the Dawson River area, 100 km by road from Callide site (~ 5 Mt CO2))
  - Enhanced Coal Bed methane recovery from the Fairview/Durham Ranch fields, 350 km by road from Callide site ~ 60 Mt CO2)
- Long-term regional CO2 storage solutions for Queensland Generators have not yet been defined.

cs energy CCSD

CO2 storage



Field Name	Storage Potential[1]	Years[2]
	t CO2	at 75 kt/yr
Mooroolo	23,000	0.3
Yandina	97,300	1.3
Yellowbank	110,000	1.5
Arcturus	136,700	1.8
Myrtleville	182,900	2.4
Rolleston	211,600	2.8
Glentulloch	433,000	5.8
Turkey Creek	922,700	12
Springvale	1,182,400	16
Merivale	3,643,500	49
Springton	7,976,700	106

Notes:

1. t CO2 based on gas and water poduction data
2. Callide oxyfuel project requires 25 - 30 kt/yr

cs energy

CCSD

Concluding comments

1. Project is now well advanced in terms of its overall development

2. Government funding for the project (nominally AUD 50 million) has been approved

3. The key activities over the next 3 months are:
   - Finalizing plant supply contract specifications
   - Completion of environmental assessment
   - Finalizing the Australian Government funding deed
   - Developing a Project Joint Venture Agreement
   - Resolving CO2 storage site selection

4. Project financial close target is end June 2007.

CO_2 free Power Plant Project – Status Oxy-Fuel Pilot Plant

IEA–GHG Oxyfuel Workshop

Windsor, USA

January 24 – 26, 2007

Lars Strömberg

Vattenfall AB

Berlin/Stockholm

VATTENFALL

The CO_2 free Power Plant Project

The Goal

To show that coal can be used in a responsible manner

- It is possible to create a coal fired power plant with “zero emissions”
- There are commercially available primary technology options in 2020
- The cost for carbon dioxide reduction is lower than 20 €/ton of CO_2
- There are even better technologies available after 2020

This will allow us to reduce the carbon emissions with 60 – 80 % until 2035 from our generation portfolio

Parallel R&D Routes Needed

- Development of the three main technologies for the 2020 target
  - Several large scale pilot and demonstration plants, optimized, with full process integration
  - Supporting R&D to reach lower costs, increase process efficiency and achieve better availability
- R&D for new and emerging technologies for deployment after 2020
  - Many routes to examine
  - Assessment to prioritize the technologies capable to overtake the leading role from any of the three main candidates.

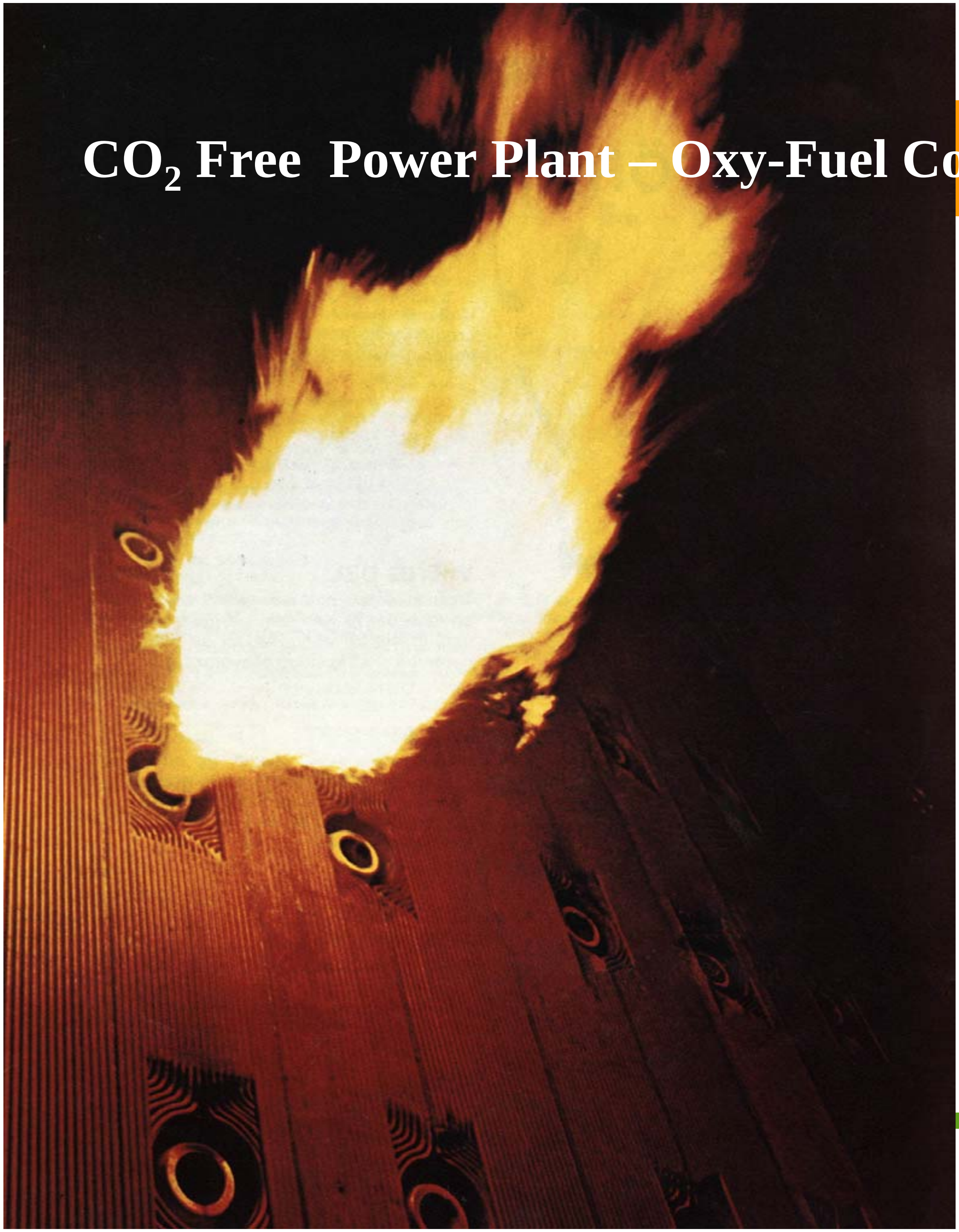
VATTENFALL

The Logics of the R&D Portfolio

R&D path	Technology	Targets	R&D efforts
Basic development for 2020 target	- Post combustion - Pre combustion - Oxyfuel	Ready 2020, 45 €/MWh, 20 €/ton CO_2	++++ + +++++++
Use of process losses	CHP processes	Fuel utilization > 85 % Lower cost	+++
Fuel flexibility and plant versatility	Circulating fluidized beds	Total fuel flexibility, co-combustion, lower cost	+
Post 2020	Chemical looping	No energy losses for separation	++
	IGWC Hybrid technologies	Higher efficiency, lower cost, hydrogen adaptive	+

VATTENFALL

CO_2 Free Power Plant – Oxy-Fuel Combustion Characteristics



The Demonstration Plant

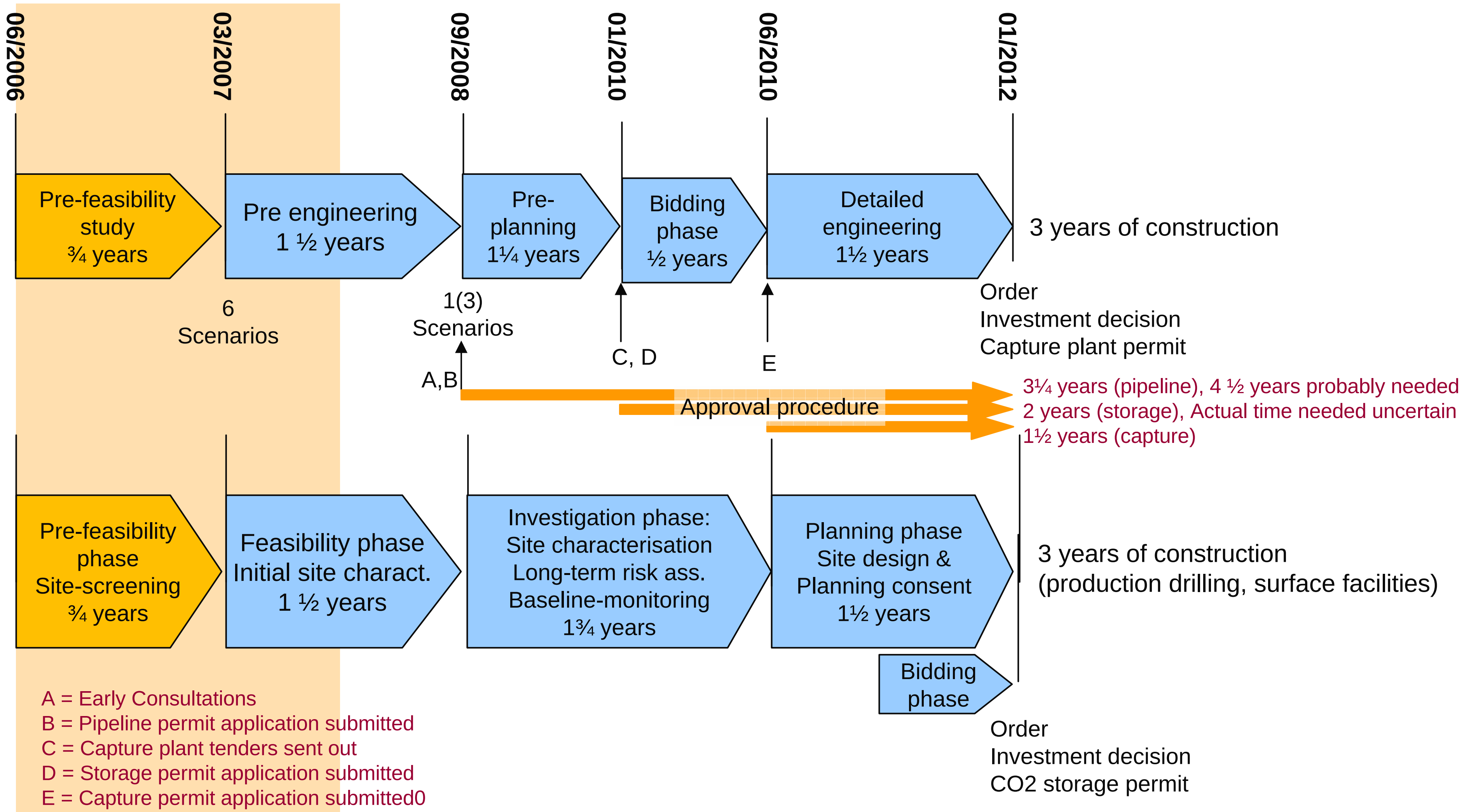
Roadmap to Realization

2006 2015 2020

Conceptual investigations	Laboratory Test	Pilot Plant	Demo-Plant	Commercial Plant
• Theoretical Research	• Research • Basic principles • Combustion characteristics	• Demonstration of the process chain • Interaction of components • Validation of basic principles and scale-up criteria • Long term charac-teristics • Non-commercial	• Verification and optimization of the component choice, the process and reduction of risks • Commercially viable incl. subsidies	• Competitive in the market at that time • No subsidies

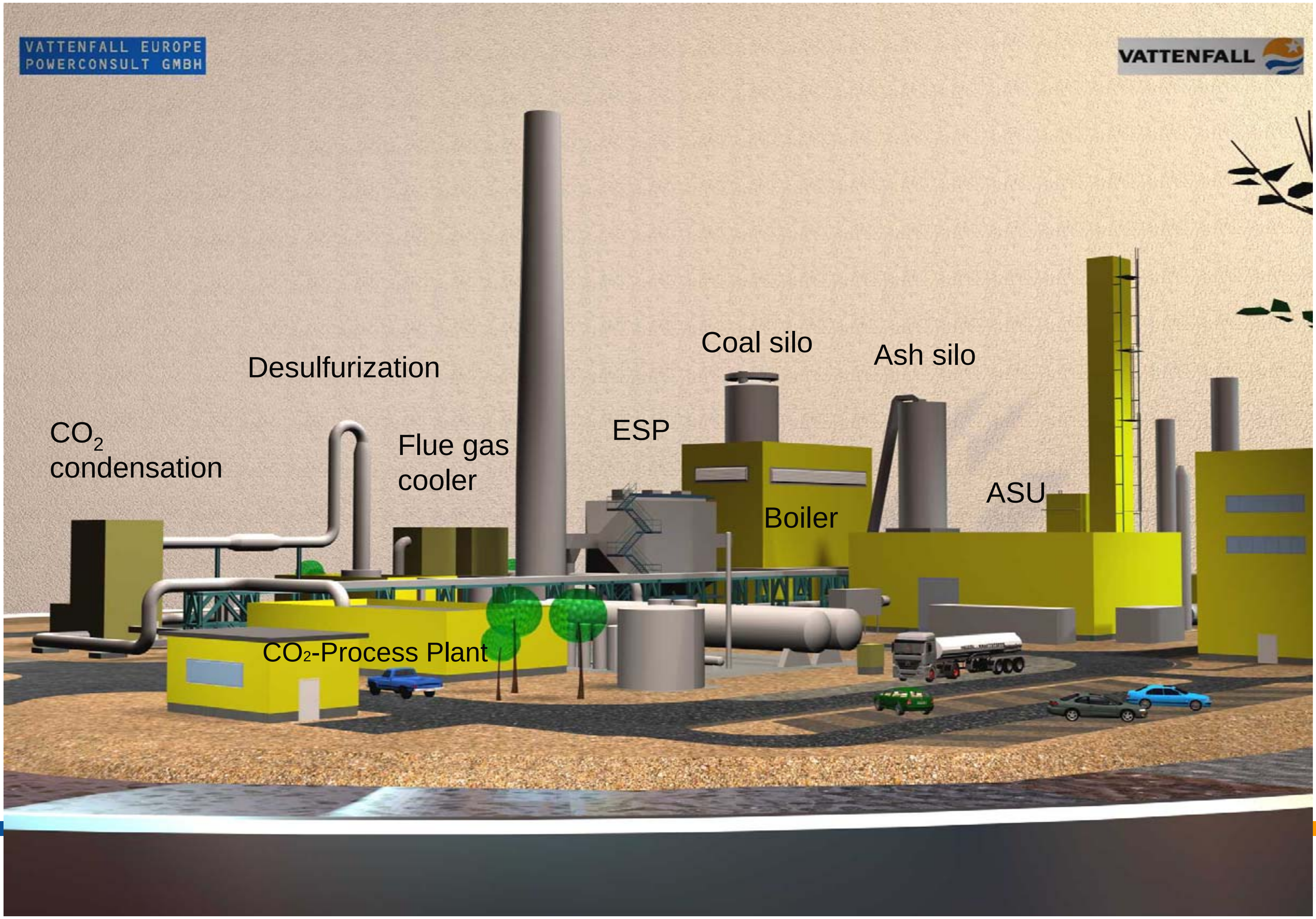
VATTENFALL

The Demonstration Project Time Line: Capture & Storage



Pilot Plant

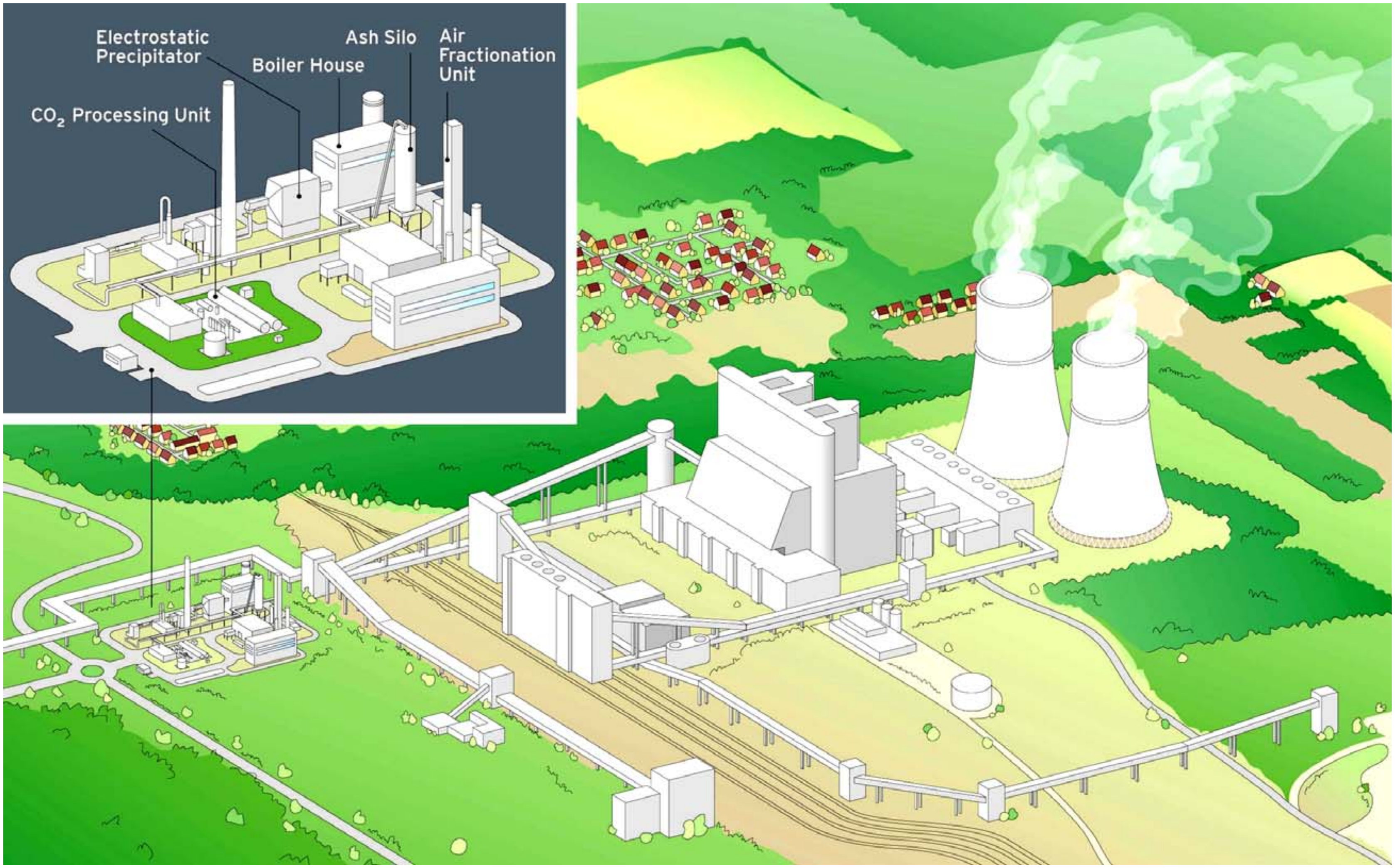
Preliminary Pilot Plant Layout



Schwarze Pumpe Power Plant

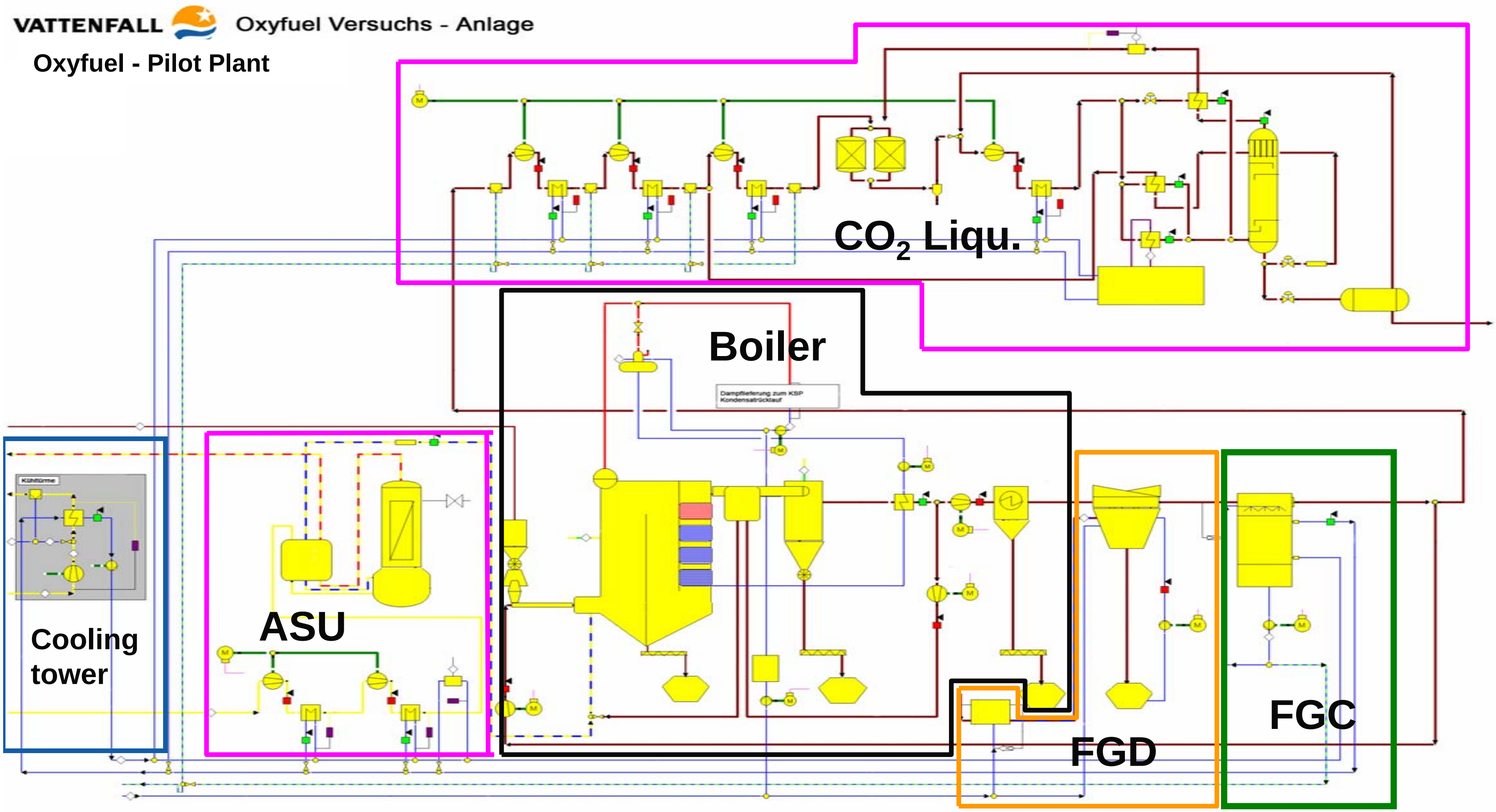
VATTENFALL

Location of the Pilot Plant at Schwarze Pumpe Power Station



Present Status

Pilot Plant Component Packages



VATTENFALL

Status – Component Packages

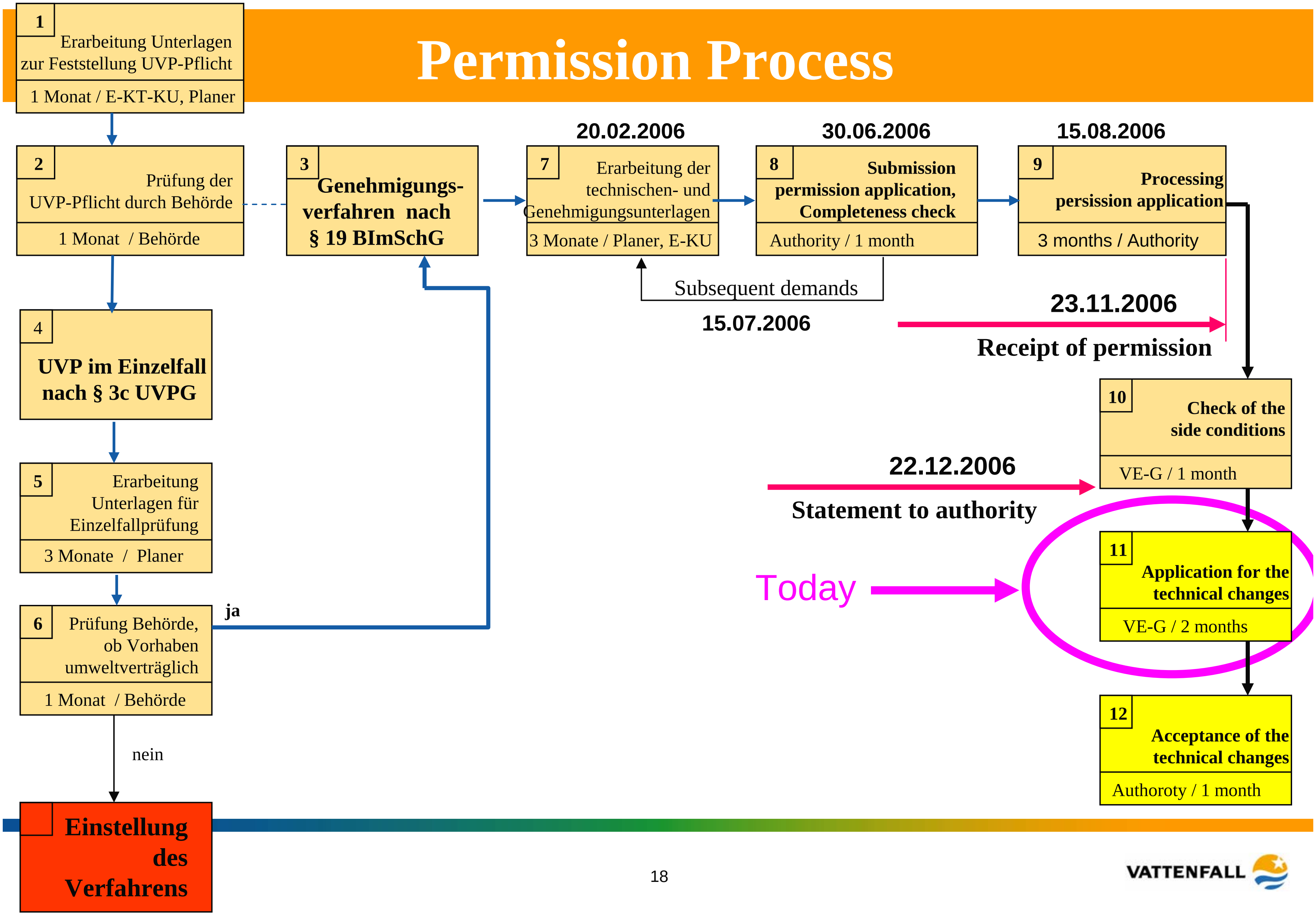
Order - lot	Supplier	Included components	Status
Boiler	Alstom	Boiler, ESP, preheater, fans, FG-ducts, stack, coal-/ash-silo	Detailed engineering
FGD	Babcock Noell	Flue gas cooler, FGD	Detailed engineering
FGC	TREMA	FGC	Detailed engineering
ASU	Linde	ASU, O2-Stand-by-system, N2	Detailed engineering
CO2-processing	Linde	CO2-cleaning, -liquefaction, back evaporation, intermediate storage	Detailed engineering
Cooling tower	GEA	Cooling tower	Detailed engineering
I & C	Siemens	Main instrumentation, control	Order Jan 2007
BOP	MCE, Berlin/CB	Pipes, fittings, pumps, insulation, Tanks, Compressed air station	Order dec 2006 Planning
Civil/Shell	OBAG Bautzen	Underground pipes, foundations, ways, building	Order dec 2007 Planning

VATTENFALL

Working Status – Enquiries and Awards

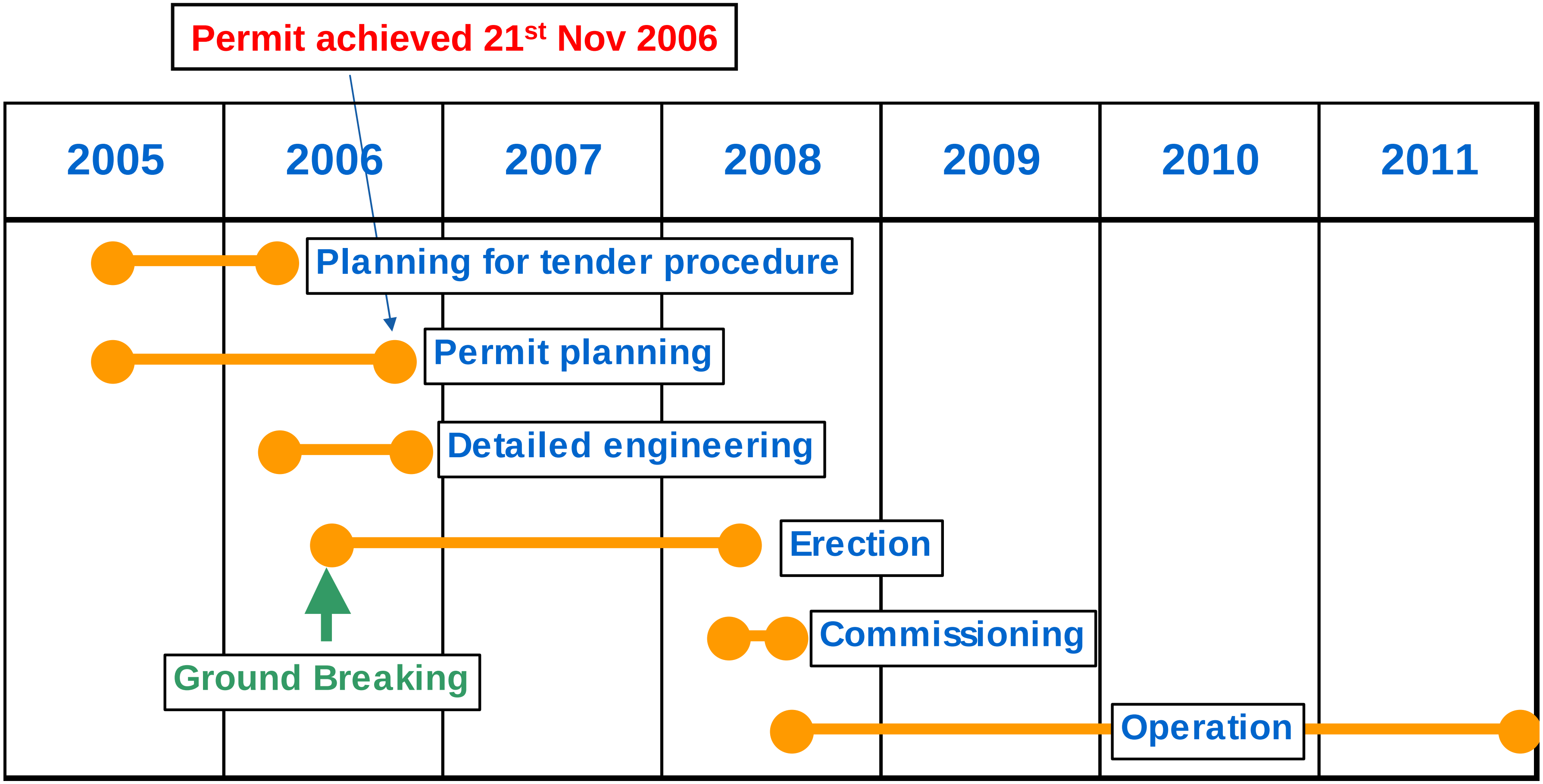
Order - lot	Included components/parts	Status
Civil	Part Extension Part Heating, climate, ventilation	Enquiry in 11/2006 Enquiry in 12/2006
Electric	Switchgears, Connection to KSP further equipments	Enquiry in 10/2006 Tendering in 12/2006
Additional equipments	Hoists	Enquiry in 02/2007

Permission Process



VATTENFALL

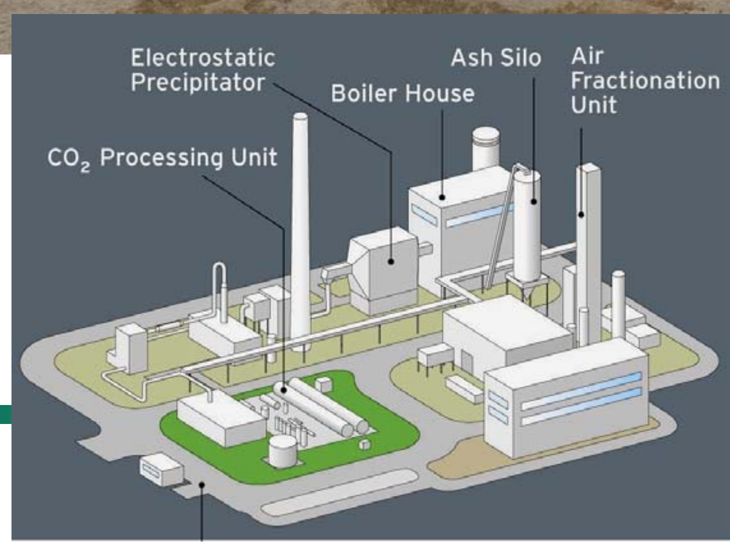
Time Schedule



Pilot Plant

The Pilot Plant's ground breaking took place in May 2006.

The plant will be in operation in July 2008

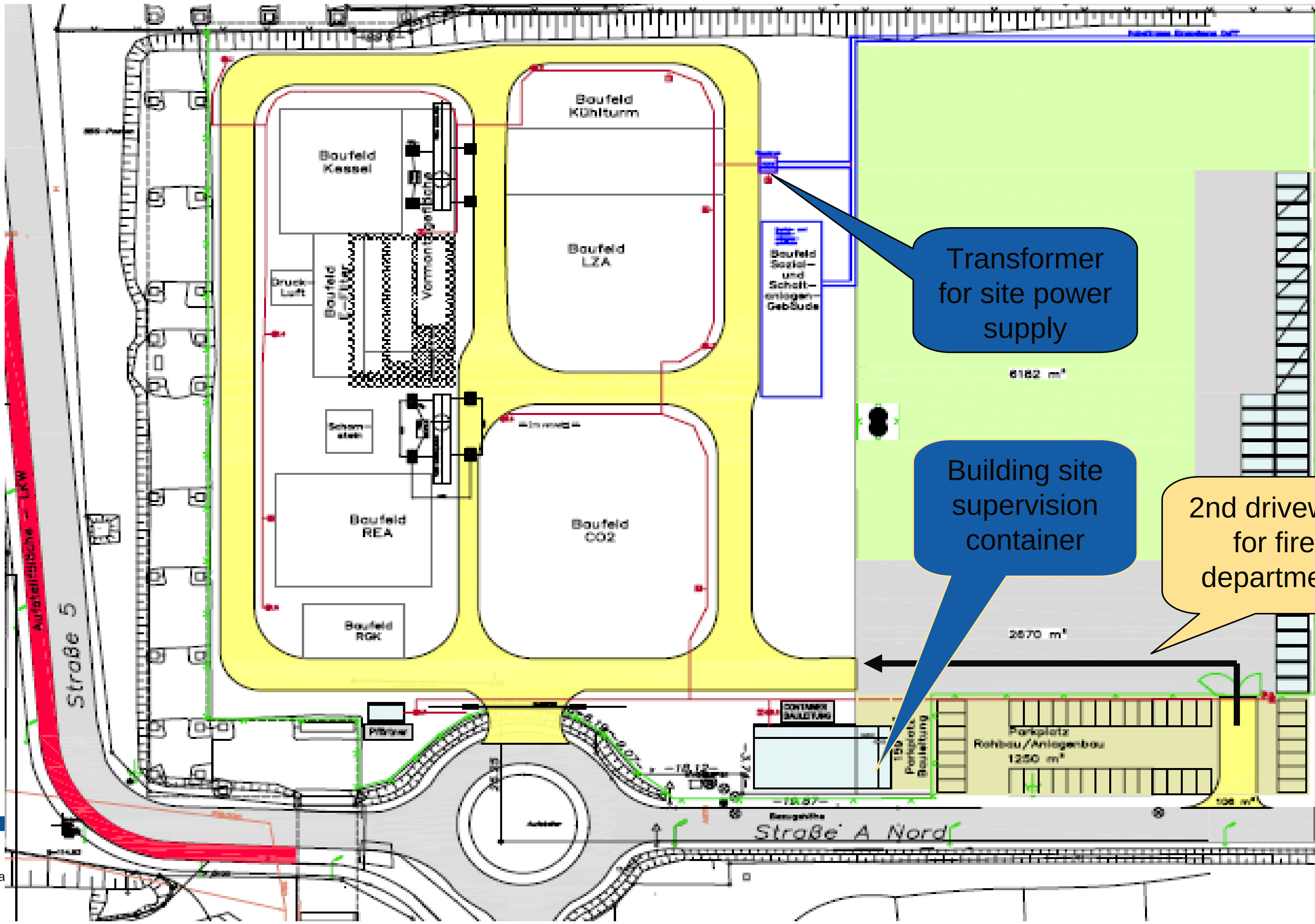


VATTENFALL

Building site – New year 2007

Building site – New year 2007

Building Site and Pre-Assembly Area

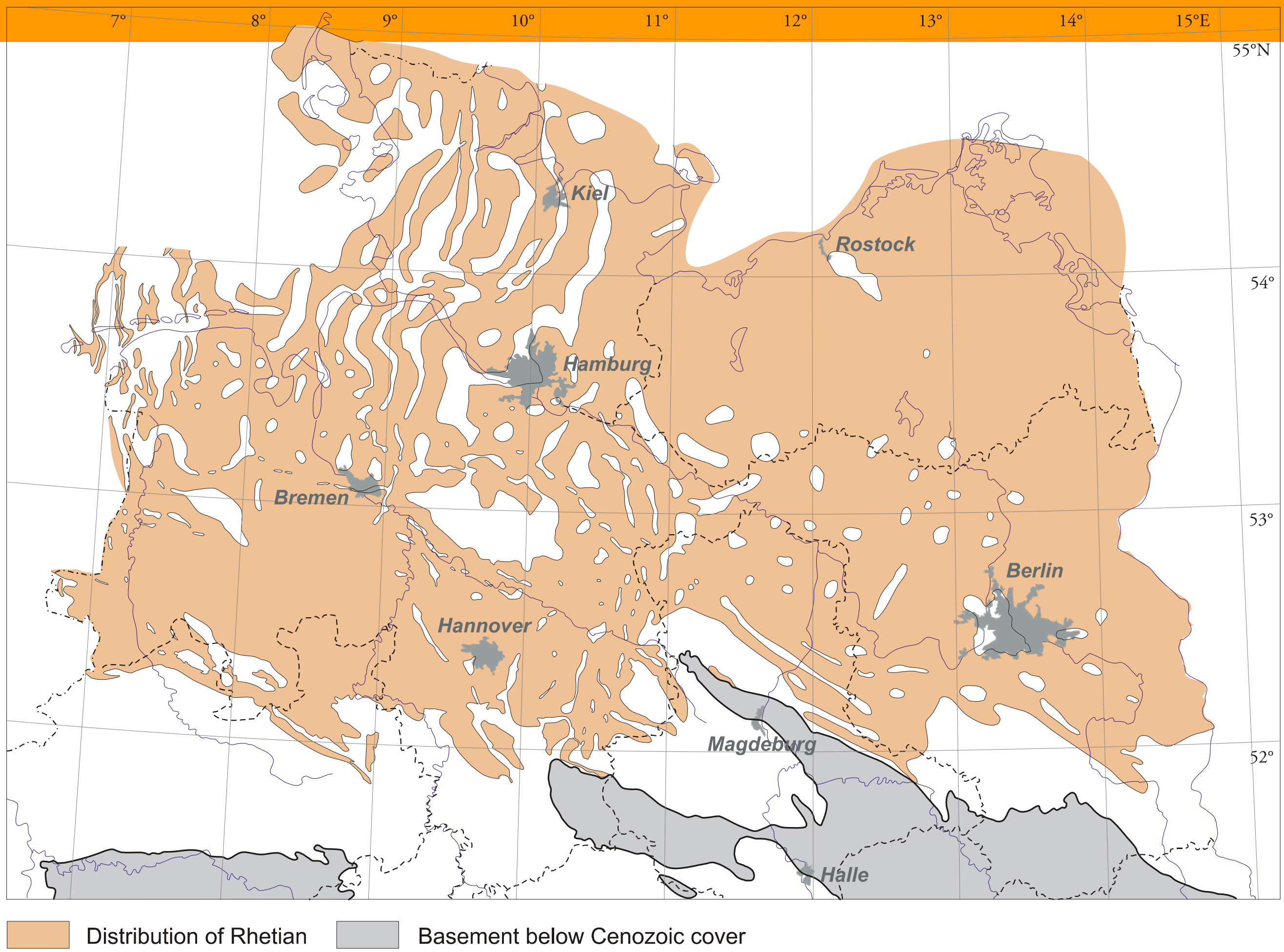


Present Status – CO_2 Storage

- The plant produces CO_2 of a very high quality
  - It can be stored anywhere, or sold as a commercial product
  - It is a product, not a waste
- Several storage options are examined at present
  - We anticipate to have a storage ready, when considerable amounts of CO_2 start to be produced

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 Eorope (and in the world) than the remaining fossil fuels

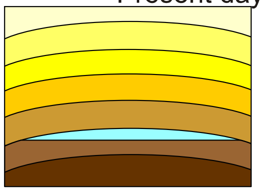
Source:

Franz May,

Peter Gerling,

Paul Krull

Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover

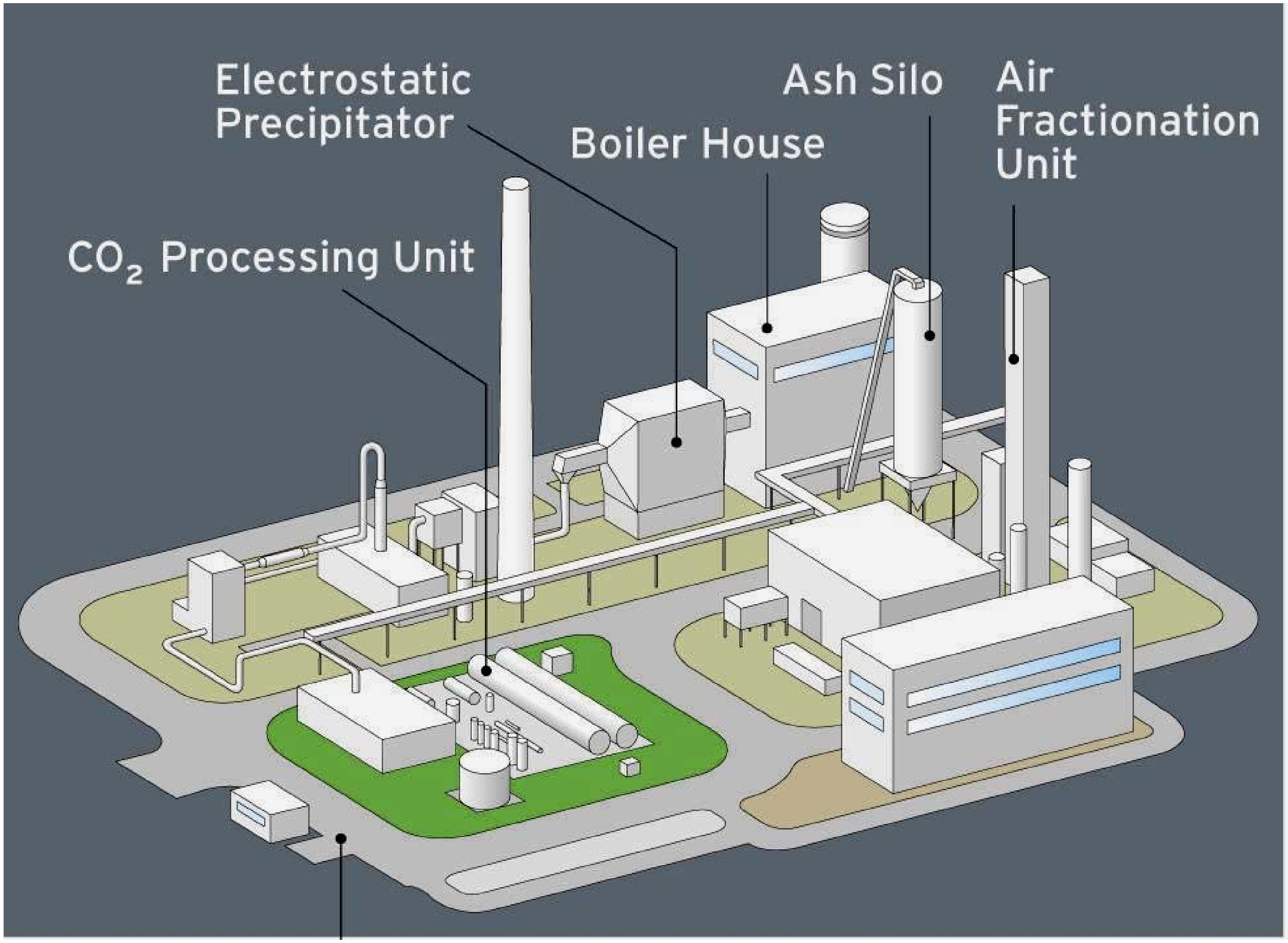


VATTENFALL

Pilot Plant Budget

- Present total budget is estimated at close to 70 million € for the investment in the plant and 23 million € for operating costs during the test period
- Vattenfall has taken decision to finance the Pilot Plant fully. There is presently no public funding at all
- We have invited partners to join us, utilizing the facility and contribute to the funding. Several have indicated participation.
- We seek partners for the storage option

Oxyfuel Pilot Plant

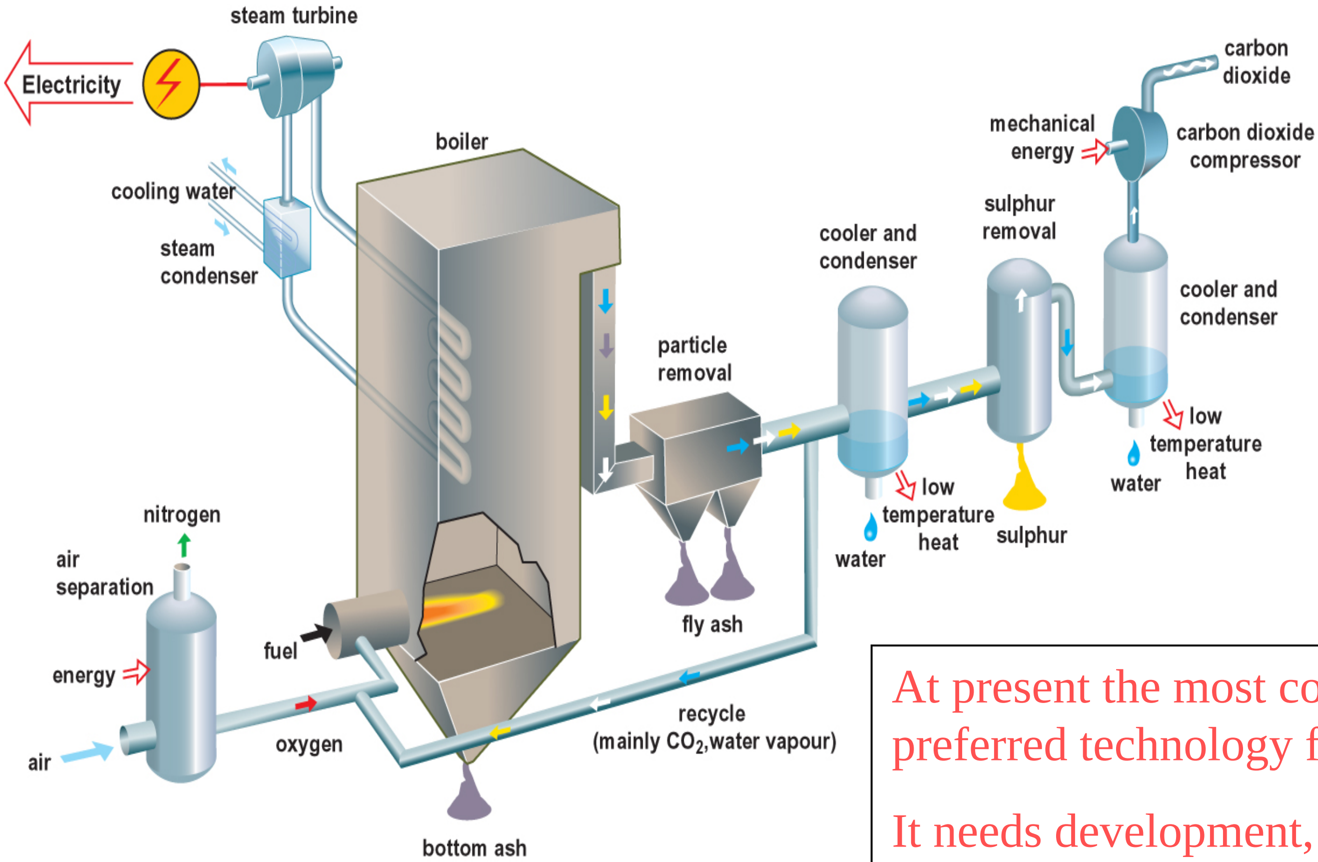


CO_2 Free Power Plant Project: Status Oxy-Fuel Pilot Plant

Back Up – Additional Slides

VATTENFALL

O_2/CO_2 combustion is the preferred option at present



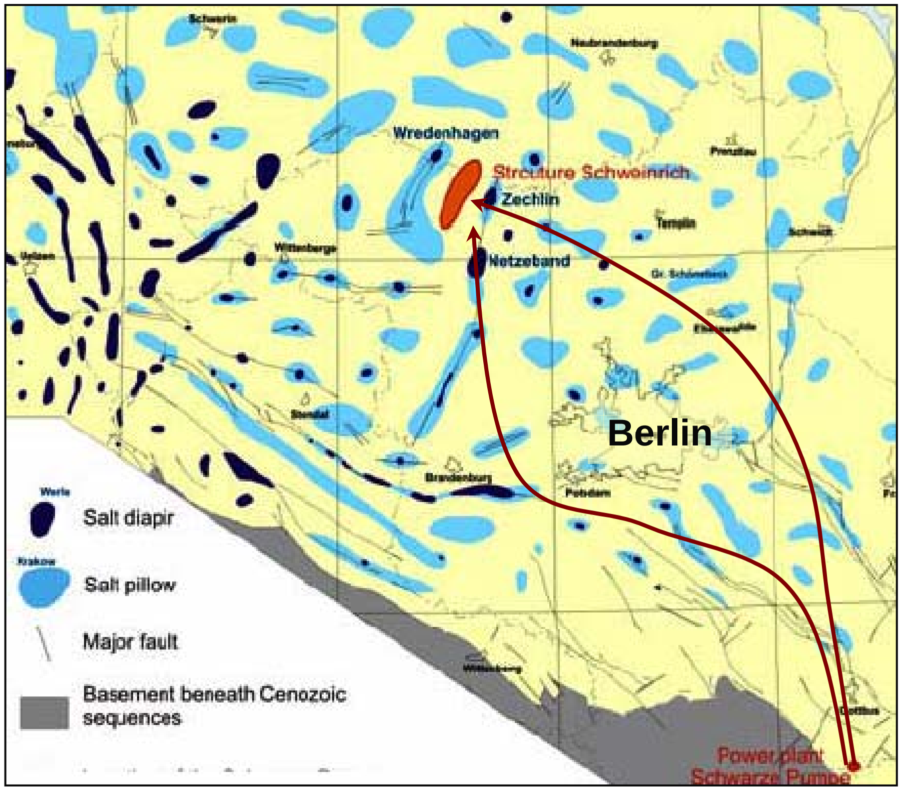
At present the most competitive and preferred technology for coal.

It needs development, pilot and demo plants to get design data

VATTENFALL

Oxyfuel projects	Characteristics	Pre combustion	Characteristics
Callide, Qld, Australia	30 MW hard coal. 2010	BP, Chevron, Carson Field, Ventura Ca, USA	400 MW. Pet Coke. EOR H2 feed to refinery.2014
Victoria, Australia	350 MW lignite. 2014	Alliance FutureGen, Tx, USA	350 MW hard coal. 2012
Sask power, Canada	350 MW hard coal. 2014	BP, GE, Peterhead, UK	Gas 350 MW, for EOR. 2010
Schwarze Pumpe	30 MWth Pilot. 2008	RWE, Germany	450 MW, Hard coal. 2014
Jupiter Oxygen, Tx, USA	45 MW Demo. 2011	E.on UK, Southern UK	350 MW, Hard Coal. EOR. 2011
Total, Lacq, France	30 MW, heavy oil. 2008	Progressive Energy, Teeside UK	800 MW, hard coal. EOR. 2009
RWE npower, Tilbury, UK	800 MW. Hard coal. 2016	Powerful, Hatfield, UK	900 MW. Hard coal. 2010. Storage ????
SEQ and ONS Energy, Drachten Holland	55 MW Hard coal. EOR. 2011	Nuon, Limburg, Holland	1200 MW, Hard coal. 2014. Storage ???
Post combustion	**Characteristics**		
Shell, Statoil, Tjellbergsodden, Norge	860 MW, Gas for EOR. 2011		
Statoil, Kårstö, Norge	230 MW, Gas for EOR. Pilot 2009. Full 2014		

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

VATTENFALL

JUPITER OXYGEN CORPORATION

MAKING ENERGY MORE EFFICIENT ◦ WWW.JUPITEROXYGEN.COM

Moving Oxy-Fuel Forward

IEAGHG International Oxy-Combustion Network

Goal of Presentation

- Moving Oxy-Fuel Forward
- Objectives of Jupiter's projects
- Learning Objective

Outline of Presentation

- Introduction Jupiter Oxygen
- Project Team
- Hammond 15 MWth burner and IPR test facility
- Slagging and Fouling
- Orrville Utilities 25 MWe power plant - OAQDA
- Economic Study with US DOE National Energy Technology Laboratory
- Summary of objectives

Introduction

In the 1990s, Dietrich Gross, Chairman and CEO of an industrial company, was concerned about the rising cost of fossil fuel and environmental issues for his business. He envisioned the use of oxygen instead of air for natural gas aluminum melting furnaces. This led to experiments with the use of oxygen in industrial melting furnaces. Knowledge from these experiments led to a new technology for combustion and burner systems for the oxy-fuel combustion process running very close to stoichiometric conditions without ambient air, which has been successfully used in industrial melting furnaces since 1997.

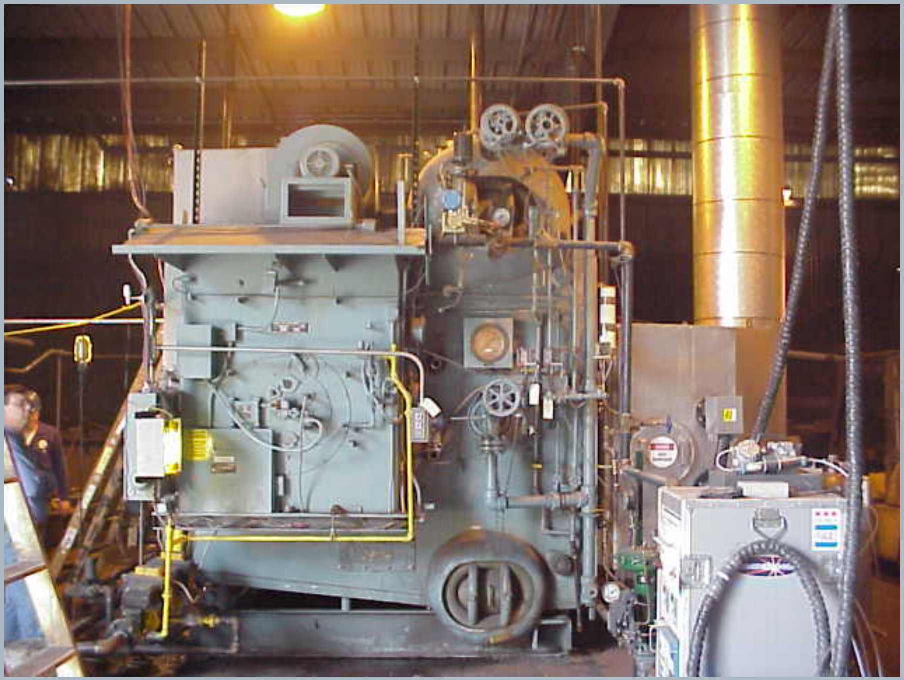
Introduction cont.

Although flame temperature exceeded 4,500° F, and reached as high as 5,300° F, industrial melting furnace process temperatures were maintained at the same levels as with conventional types of combustion without damage. The molten metal process temperature remained about 1,400° F, with wall temperatures about 1,800° F, and stack temperature about 1,000° F.

JUPITER OXYGEN CORPORATION

MAKING ENERGY MORE EFFICIENT ◦ WWW.JUPITEROXYGEN.COM

Jupiter Oxygen Past Testing



Summary of Results with Jupiter Oxygen as a Stand-alone

- Efficiency increase for the boiler on the order of 5 to 12%, even on retrofit applications
- Decrease in fuel usage up to 16%
- Nitrous Oxides production of 0.088 lbs/mmbtu, without the need for back end technology, expectation for below 0.05
- Across the board reduction of all pollutants due to fuel reduction
- Lower cost and higher efficiency of running current back end equipment

Results with Jupiter Oxygen and Integrated Pollutant Removal

- No need for NO_X control technology
- Capture of more then 80% of the CO_2, at a pressure which shows at least 95% can be captured
- 60 to 90% mercury capture (range due to test measurement limitations)
- 99% sulfur removal
- 99% removal all particulates, with 80% removal of the small particles (PM 2.5)

Project Participants

- Jupiter Oxygen
- Doosan Babcock LLC
- Orrville Utilities
- OAQDA – Ohio Air Quality Development Authority
- USDOE – National Energy Technology Laboratory
- Maxon Corporation
- Coalteck LLC
- Michigan State
- Purdue University
- University of Wyoming

15 MWth Hammond Test Facility

- Primary Function
  - Oxy-fuel burner test system
  - Integrated Pollutant removal research
  - Flue Gas re-circulation
- Major Components
  - Chamber for the continuous operation of 15 MWth oxygen burner
  - 105 TPD cryogenic plant – 95% purity
    - Onsite availability of 99+% if needed
  - Coal pulverizer with recirculation system
  - Automated Data Acquisition system

Hammond Test Facility Oxygen Supply

Test Facility Initial Objectives

- Single burner firing at a rate of at least 15 MWth
- Flame stability with recycled flue gas moving PC coal to burner tip
- Ultra-Low NO_X levels
- Integrated Pollutant Removal system data collection
  - Characteristics

Testing and data acquisition

- Per AMSE standards
- Burner
  - Fuel Analysis
    - Ultimate
    - Proximate
    - Mineral Composition
  - Mass Flow
  - Velocity (two-phase flow)
  - Particle Size
  - Entrained Air
- O_2 flow
  - Temperature, Pressure, Mass and Velocity
- CO_2 (re-cycled flue gas)
  - Temperature, Pressure, Mass and Velocity
- Flame
  - Dimensions
  - Heat transfer Characteristics
    - RTD's and Thermocouples
    - Radiometer
    - Optical Pyrometer
- In furnace gases
  - Temperature
  - Pressure
  - Composition (Vapor and Particle)

Testing and data acquisition cont.

- **Tubes**
  - Temperatures
  - Destructive testing
- **Water**
  - Inlet, Temp., Pressure, Mass Flow
  - Tubes, Temp., Pressure, Velocity (calc.) Mass flow (measured)
  - Outlet Temp. Pressure, Mass Flow
- **Flue Gas**
  - Temperature
  - Pressure
  - Composition
    - Vapors
    - Particles
    - Hg
    - Moisture
  - Ash and Slag
  - Pulverizer all variables per ASME

IPR testing and Data acquisition

- **Dust Collector**
  - Inlet (temp., pressure, composition)
  - Within (temp., pressure)
  - Outlet (temp., pressure, composition)
- **Direct contact heat exchanger 1**
  - Gas
    - Inlet (temp., pressure, dew point)
    - Outlet (temp., pressure, dew point, composition, velocity, coupon-corrosion)
- **Liquid**
  - Inlet (temp., pressure, mass flow, chemical reagent flow, composition- pre and post injection)
  - Column (temp., pressure)
  - Outlet (temp., pressure, volumetric flow rate (timed capture), composition (jar sample)
- **Heat exchanger 2 – Same**

IPR testing and Data acquisition cont.

- Compressor 1
  - Inlet (corrosion coupon, temp., pressure)
  - Intercooler (gas temp. in/out, cooling water in/out)
  - Outlet (corrosion coupon, temp., pressure)
- Compressor 2 – Same
- Compressor 3 – Same
- Hg oxidation/removal
  - Power consumption
  - Temperature
  - Digestion
  - Outlet (pressure, temperature)
- Capture Vessel (temp., pressure composition
- Exit vent (temp., pressure, velocity, composition)

15 MWth Summary

- Burner
  - Performance
  - Characteristics
- Recycle
  - Process variables
  - Characteristics
  - Performance
- IPR
  - Performance
  - Characteristics
- Status
  - Being constructed

Slagging and Fouling

Site Specific – Orrville and Hammond

Objective – To establish whether or not the proposed approach will give rise to significant changes in fly ash quality and in ash deposition behavior

Background – Question: with higher peak flame temperatures, higher oxygen partial pressures and that the time-temperature history of the flue gases and ash particles down stream of the burners may be different

Expectation – in spite of differences in the combustion conditions (above) for oxy-fuel firing, it is expected that the slagging and fouling behaviour in coal fired plant can be managed using existing sootblowers without any negative impact on plant operation

Slagging and Fouling Reportage

- Discussion of the ash-related issues associated with oxy-fuel firing
- Assessment of the risks of significant ash-related impacts on the plant performance and integrity associated with the conversion of the Orrville plant to oxy-fuel firing

Orrville Utilities

<u>Boiler 13</u>

- Combustion Engineering
- Model VU-40, pressurized w/regenerative air heater & ESP (rebuilt 1994)
- MCR rating 260,000 lbs/hr @ 1270 PSI, 925 F SH, 301.8 MMBtu/hr (365.4 MMBtu/hr permitted)
- PC, (4) Type RO burners, gas ignitors, front wall fired, dry bottom
- (4) Burners
- (2) Raymond 523 pulverizers
- 25 MW steam turbine-generator
- Installed 1969

The facility at Orrville, OH.

Orrville Utilities

- The main air compressor for the plant (MAC) is a Hitachi 4 stage Model 1 DHB-GH (DH-80) Dry with an inlet 12.4 psia @85 Deg F, Discharge 88.9 psia @95 Deg F.
- The driver is a Siemens 8000 HP, 1200 RPM, 3/60/13200, PF 0.80. The expander is an APCI: ETAEG-6. The plant also includes two 60,000 gallon LOX storage tanks.

cryogenic plant

IPR System – Slip Stream

- As specified
  - 25% mass flow of flue gas for to IPR system multiple compression with recovery
- Using existing dust collector before IPR
- Wet heat exchangers
- Bypass arrangement
- Variable product capability

Burner and Re-circulation System

Burner

- Tested at Hammond
- Maxon coal and oxy design, previously tested at Jupiter Oxygen
- Staged oxygen for lowest NO_X

Re-circulation

- After existing dust collector
- Removal of some SO_X
- Removal of other products of combustion
- Reasons
  - Move coal to burner
  - Balance heat transfer

Current Status

- Burner – Prototype constructed to be tested at Hammond
- Boiler
  - PFD (re-circulation, SO_X removal, and IPR mass flow)
  - Site Data Collection
  - Thermal Model set-up & Iteration
  - Heat Flux / Water wall temperature calculations
- IPR
  - Multiple vendor quotations compression equipment
  - Multiple vendor quotations heat exchangers and other components

Current Status continued

- Re-circulation de-SO_X equipment
  - Multiple process packages considered
  - Multiple vendor quotations received
- Oxygen generating plant
  - Plant available for use
- Regulatory
  - Active
- Equipment review, February and March 2007

Economic Study - Objectives

1. Hypothetically assess the economic feasibility of retrofitting an existing subcritical, pulverized-coal (PC) fire unit with Jupiter's Oxy-fuel process with the NETL's Integrated Pollutant Removal (IPR) Process
2. Assess the individual merits of Jupiter's technology with a generic CO_2 compression methodology

Cost Considerations for Study

- Capital
  - Oxygen Plant
  - Burners
  - Flue Gas Recirculation
  - Integrated Pollutant Removal System
- Capital Costs Avoided
  - SCR
  - Conventional FGD and Mercury (IPR Process)
  - MEA equipment with compression
- Gross Capital Costs vs. Base vs. Similar results
- Operating Costs
  - Electricity or Steam Value
  - Other Cryogenic Plant costs, Other IPR Costs
- Operational Savings or Avoided Costs

Economic Results Discussion

- High Degree of in-depth discussion on the economic issues associated with each case
- Compare and describe these results with past similar background studies
- Describe advantages and disadvantages of the Jupiter Oxygen Process and the IPR process separately and in combination from an economic perspective

JUPITER OXYGEN CORPORATION

MAKING ENERGY MORE EFFICIENT ◦ WWW.JUPITEROXYGEN.COM

Visionary Innovation | Scientific Approach | Operational Experience

WEB:
www.jupiteroxygen.com

CONTACT US:

Mark K. Schoenfield, Senior *Vice President - Operations & General Counsel*
Jupiter Oxygen Corporation
4825 N. Scott St., Suite 200, Schiller Park, IL 60176
PHONE: 219 712 5206 **FAX**: 847 928 0795
EMAIL: m_schoenfield@jupiteroxygen.com

Harold Green, *Vice President Public Affairs and Communications*
Jupiter Oxygen Corporation
5011 Victor St., Dallas, TX 75214
PHONE: 214 789 5777 **FAX**: 214 821 3000
EMAIL: haroldg@vzw.blackberry.net

Thermo-acoustic Instabilities in a CO_2 Diluted Oxy-Fuel Combustor

Study under the Norwegian Research Council funded program KLIMATEK

Mario Ditaranto, Jørgen Hals

SINTEF Energy Research

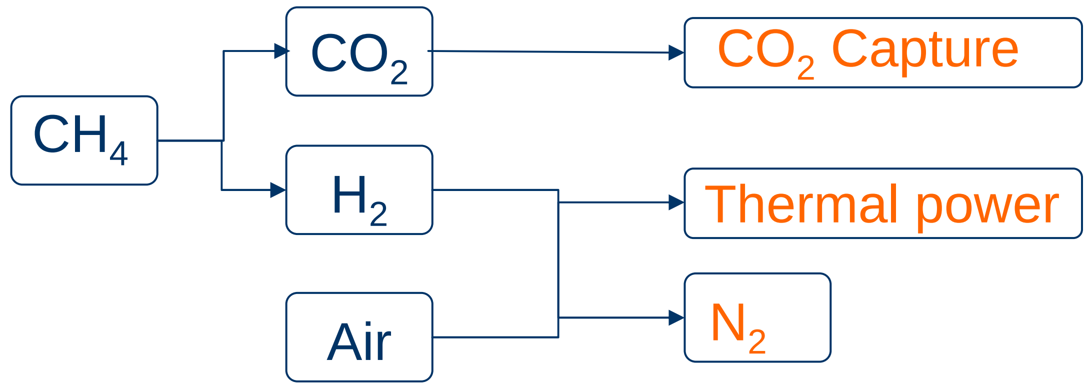
2nd IEAGHG Oxy-Fuel Workshop,

January 25th-26th, 2007

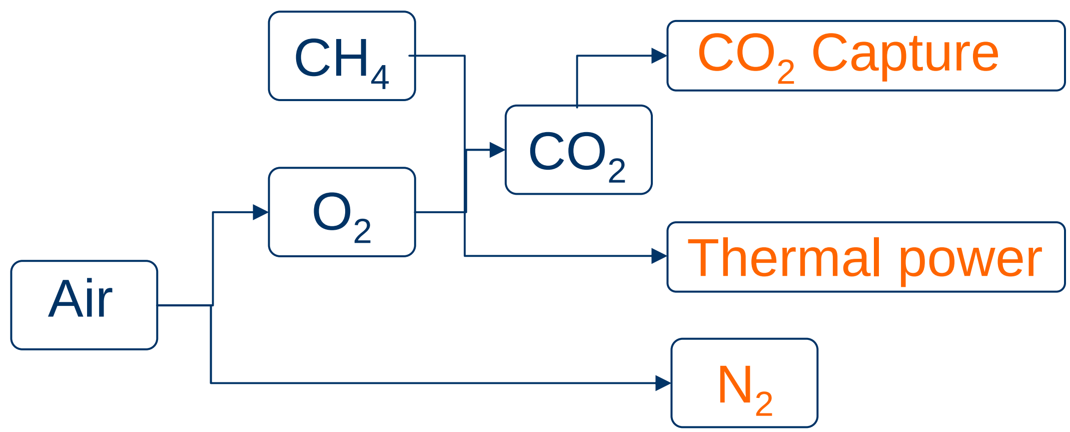
CO_2-free Power Generation Cycles

Hydrogen Combustion

(pre-combustion)



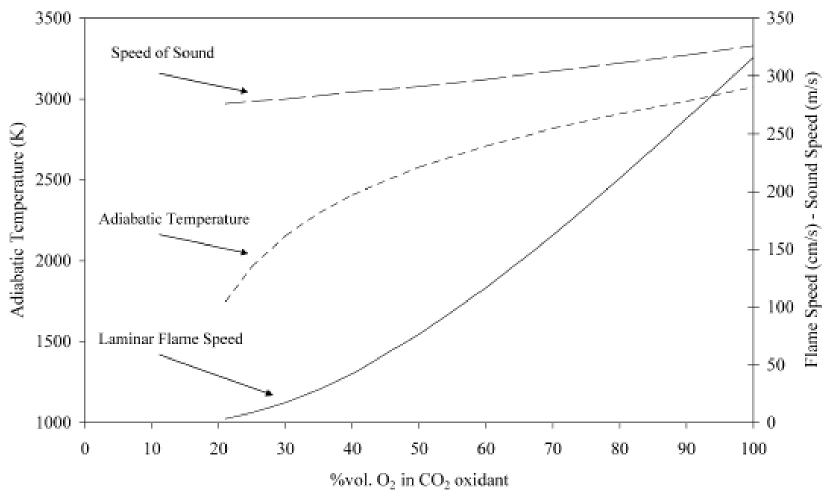
Oxy-Fuel Combustion



Ditaranto & Hals / 2nd IEAGHG Oxy-Fuel Workshop, 2007

Oxy-fuel Combustion in Gas Turbine

- Years of experience for air-supported combustion
- Stoichiometric combustion
  - temperature
- CO_2 injection/dilution
  - mixing, stability, heat transfer
- Unusual properties
  - temperature, laminar burning velocity, stability



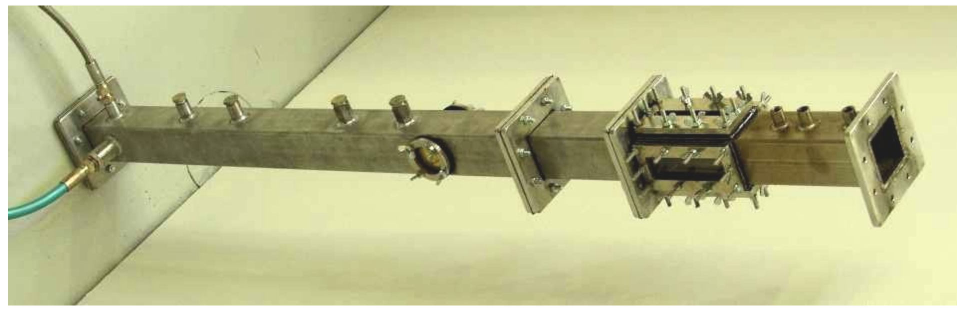
Ditaranto & Hals / 2nd IEAGHG Oxy-Fuel Workshop, 2007

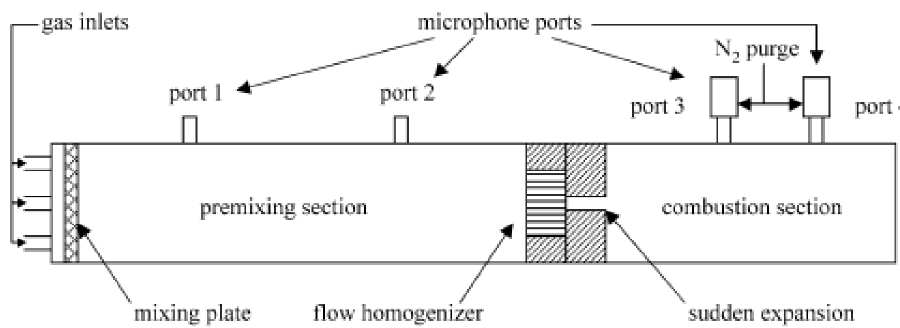
Thermo-acoustic Instabilities

- Consequences
  - flame blow off – flashback
  - vibrations / structural damage
- Industrial problems encountered in:
  - Premixed type low NOx combustors
  - Rockets, …
- In oxy-fuel GT?
  - Additional control of CO_2 dilution / O_2 enrichment allows more possibilities for "zoning" the flame, however:
  - Chemical timescale and strong heat release rate are critical for thermo-acoustic interactions

Experimental Setup

- 2D sudden expansion (exp. ratio: 10)
- Premixed combustion
- Oxidant:
  - Air
  - variable O_2/CO_2
- Fuel: CH_4
- Parameters:
  - Re: 500 – 5000
  - ER: 0.6 – 1.2
  - O_2 content



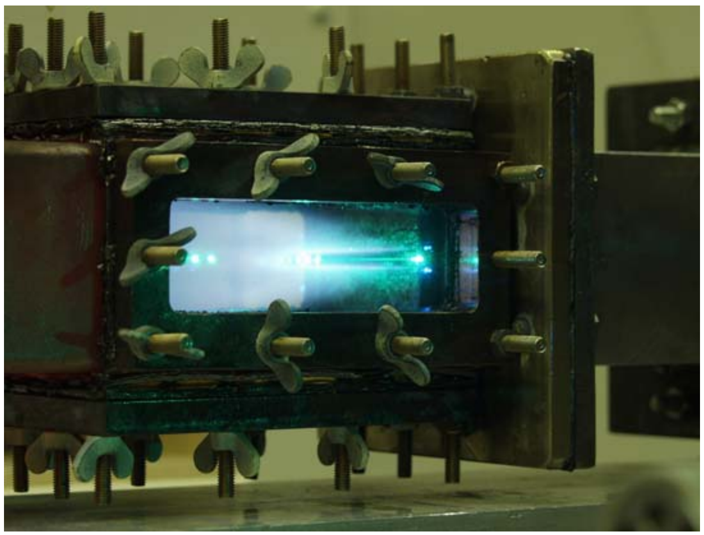


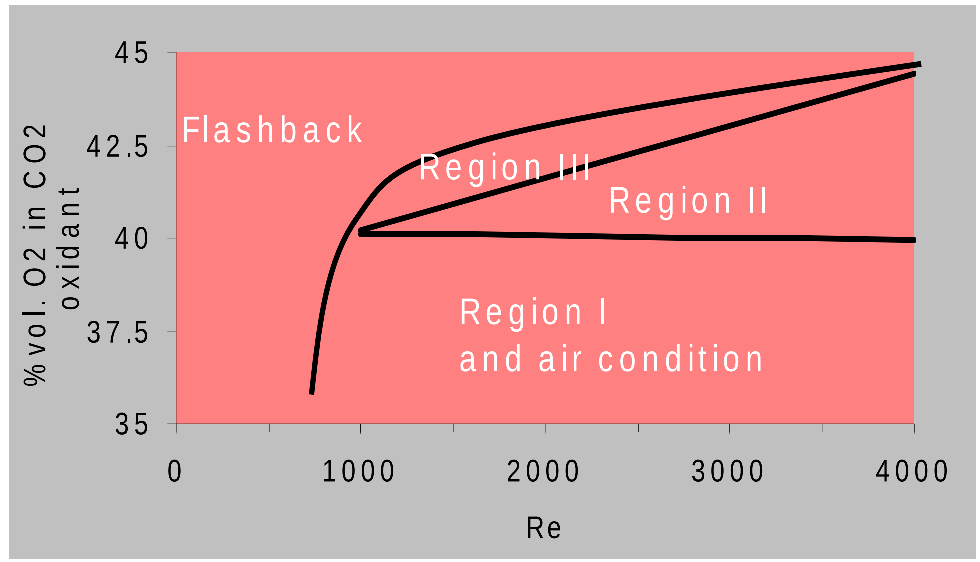
Measurements

- **Acoustic pressure** in combustor and premixer sections
  - flush-mounted microphones
- **CH* chemiluminescence** (heat release rate)
  - PM tube and filtering at 431 nm +/- 10 nm
  - 2D by filtered imaging
- **Velocity**
  - locally by Laser Doppler Velocimetry
- **Temperature**
  - wall and exhaust gases by thermocouples

Oxy-Fuel Flame Stability Pattern

- At constant equivalence ratio (0.9)



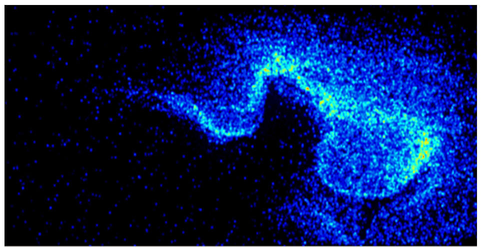


Ditaranto & Hals / 2nd IEAGHG Oxy-Fuel Workshop, 2007

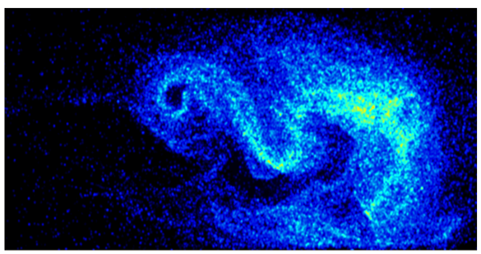
Region I: LF Fluid Mechanical Mode

- Weak acoustic - combustion coupling
- large-scale motion controls flame structure
- No well defined cyclic motion of the flame structure

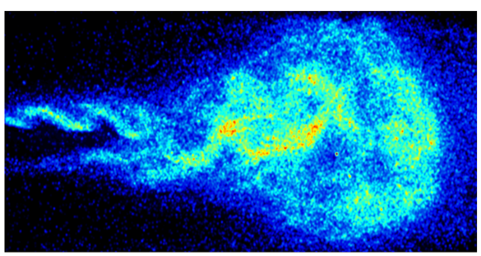
- Re = 800

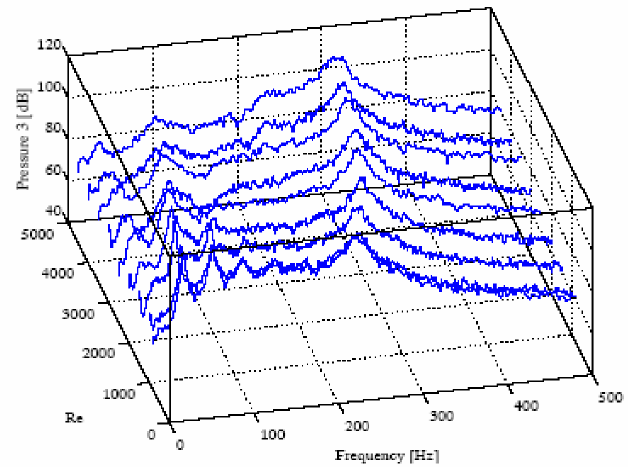


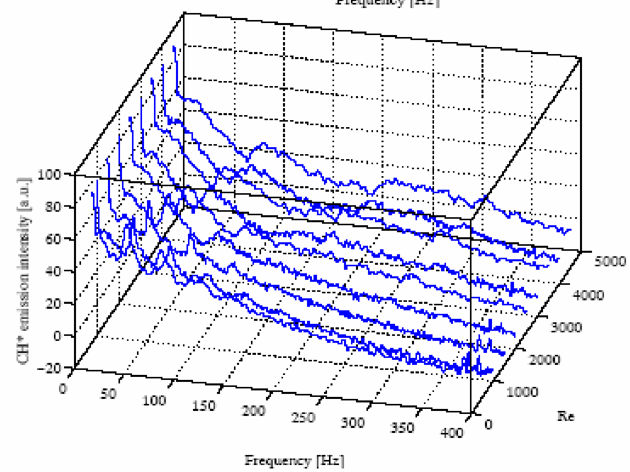
- Re = 1500



- Re = 2500



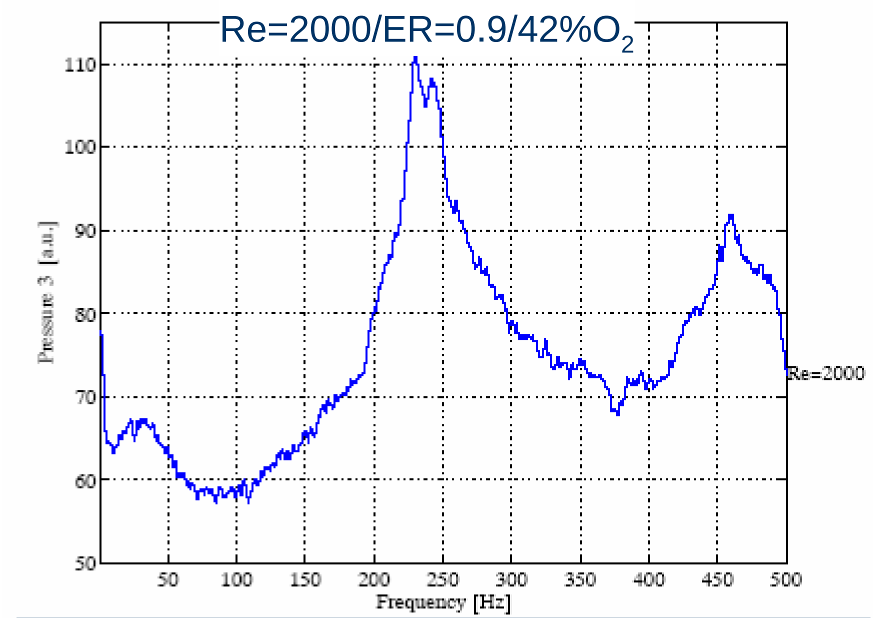


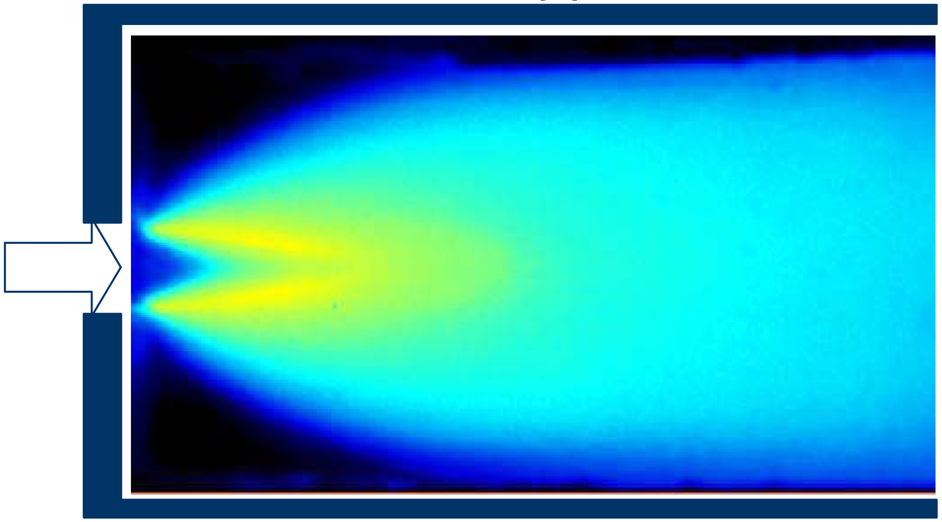


Ditaranto & Hals / 2nd IEAGHG Oxy-Fuel Workshop, 2007

Region III: Thermo-Acoustic Mode

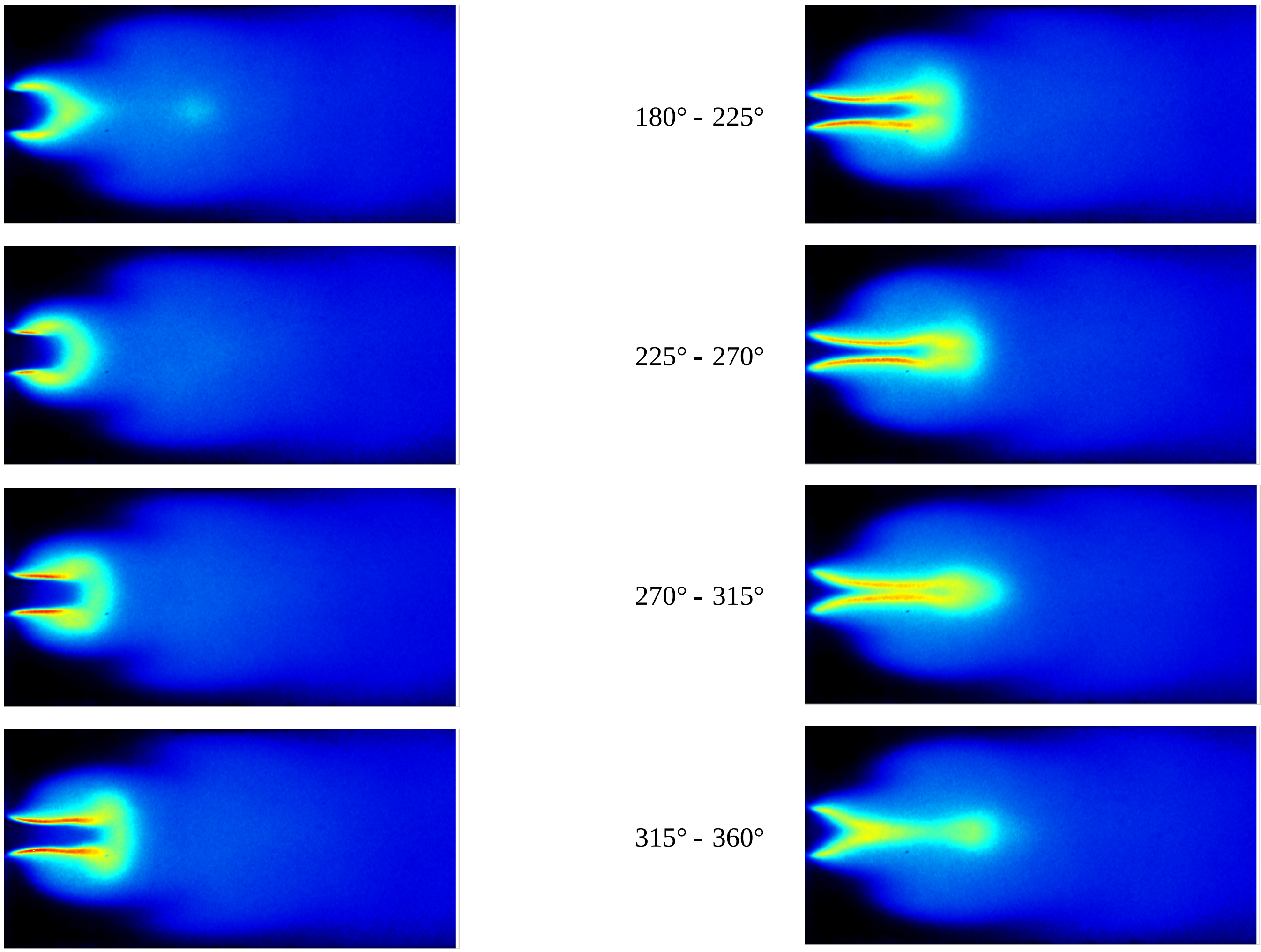
- Strong thermo-acoustic interaction at a characteristic acoustic mode of the system
- Violent consequence of enhanced combustion properties
- Combustion controls the flow pattern
- Heat release is concentrated at the expansion region





Ditaranto & Hals / 2nd IEAGHG Oxy-Fuel Workshop, 2007

Region III:
Full phase - averaged periodic cycle

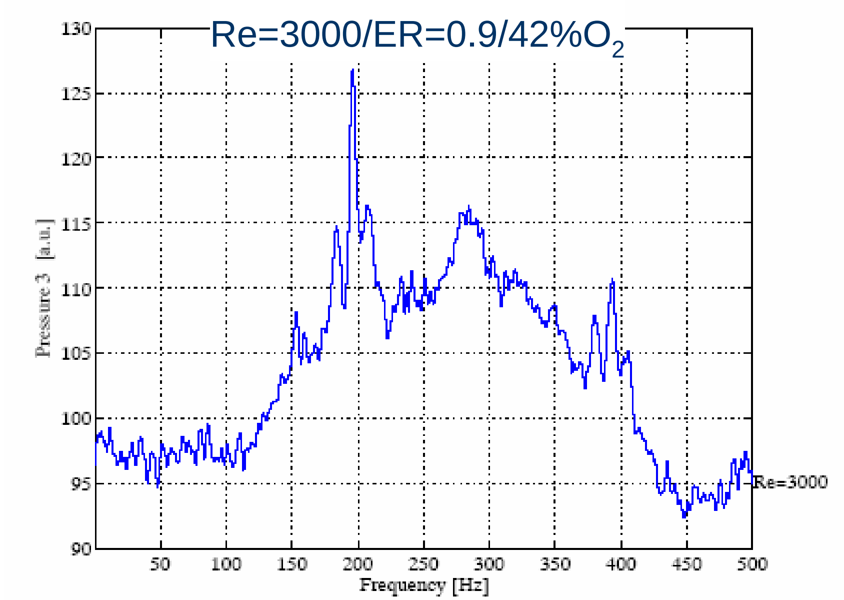


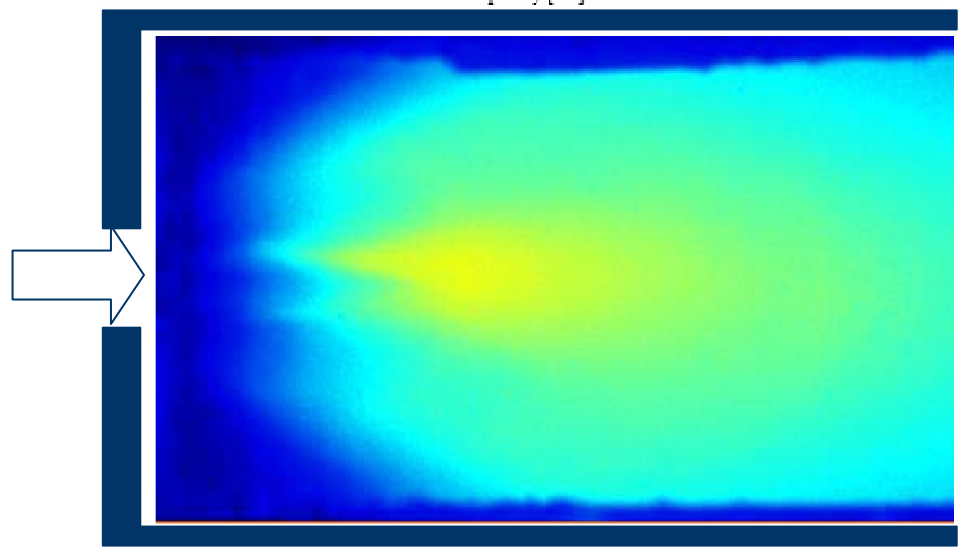
0 - 45°
45° - 90°
90° - 135°
135° - 180°
180° - 225°
225° - 270°
270° - 315°
315° - 360°

Ditaranto & Hals / 2nd IEAGHG Oxy-Fuel Workshop, 2007

Region II: Thermo-Acoustic Mode

- Strong thermo-acoustic interaction at a characteristic acoustic mode of the system
- Flame pattern is different than Region III
- Combined combustion and momentum controlled pattern

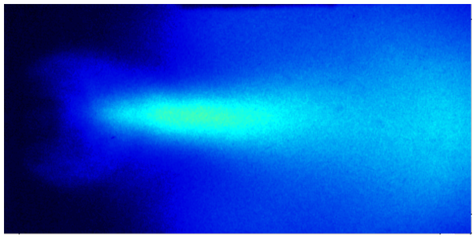




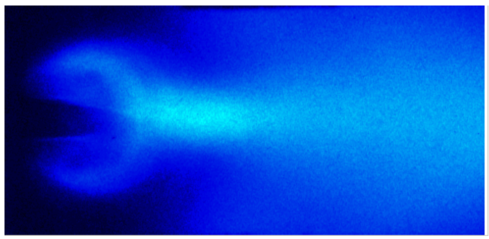
Ditaranto & Hals / 2nd IEAGHG Oxy-Fuel Workshop, 2007

Region II:
Full phase - averaged periodic cycle

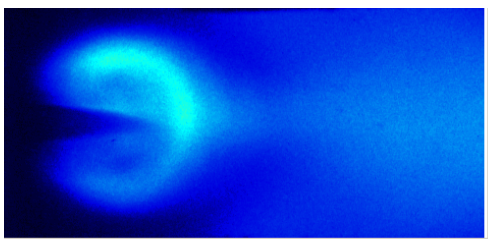
0 - 45°



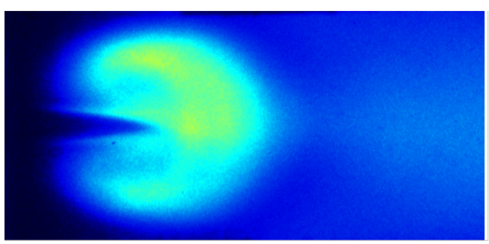
45° - 90°



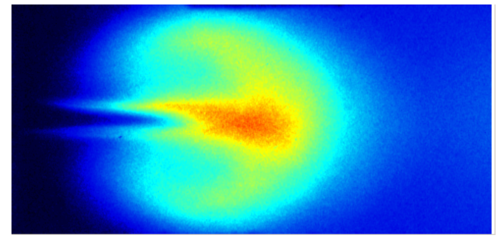
90° - 135°



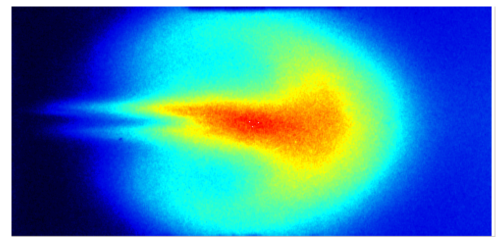
135° - 180°



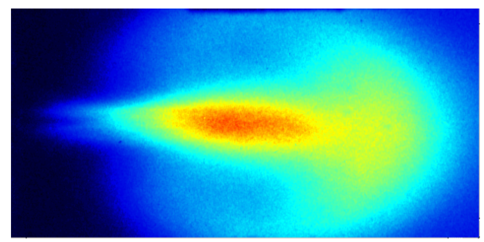
180° - 225°



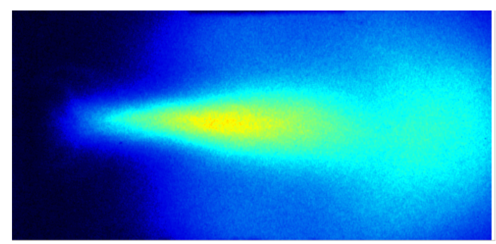
225° - 270°



270° - 315°



315° - 360°



Ditaranto & Hals / 2nd IEAGHG Oxy-Fuel Workshop, 2007

Mode Selection

- Heat release rate model:

$$\frac{q'(x,t)}{Q'} = \alpha_{q-u} \frac{u'(x,t-\tau_{q-u})}{U}$$

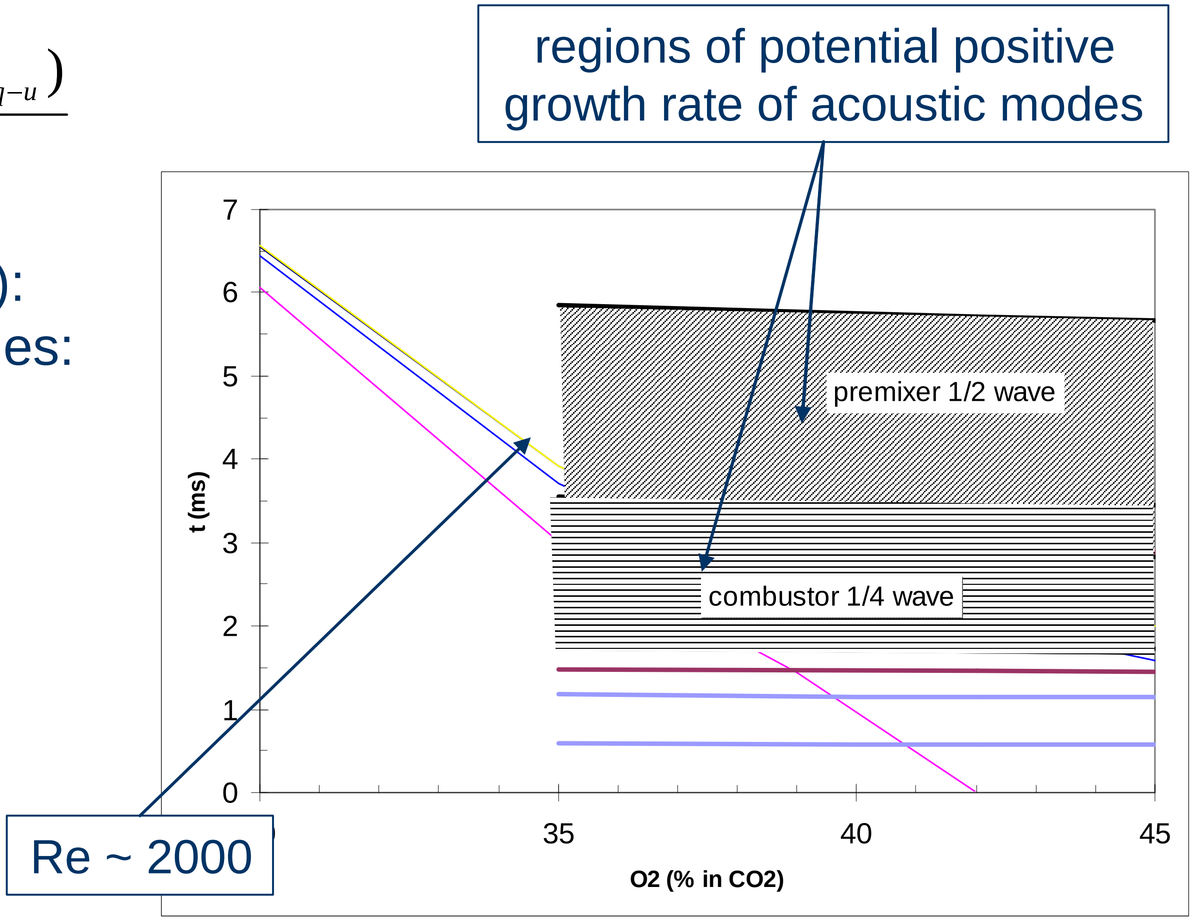
- Time lag (attached flame!): convection + chemical times:

$$\tau_v = \frac{H}{4S_l}\sqrt{1-\frac{S_l^2}{U^2}}$$

- Conditions for Rayleigh criterion:

$$\tau_v \in \left[\frac{1}{2f_{\lambda/4}};\frac{1}{f_{\lambda/4}}\right]$$

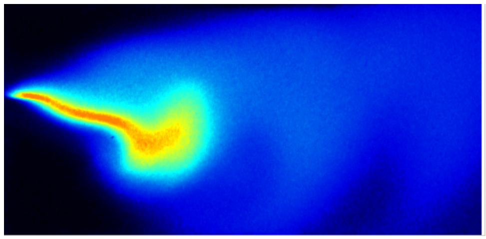
$$\tau_v \in \left[\frac{1}{2f_{\lambda/2}};\frac{1}{f_{\lambda/2}}\right]$$



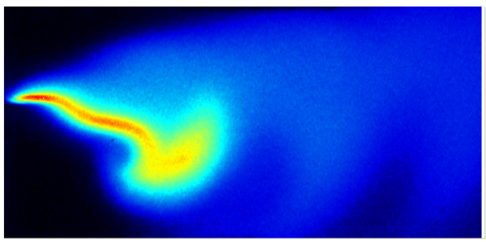
Ditaranto & Hals / 2nd IEAGHG Oxy-Fuel Workshop, 2007

<u>Overlapped Region II and III</u>:
Full phase - averaged periodic cycle

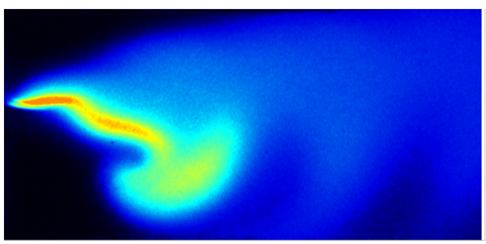
0 - 45°



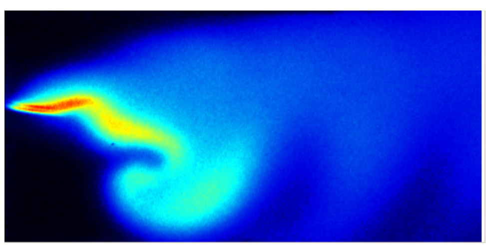
45° - 90°



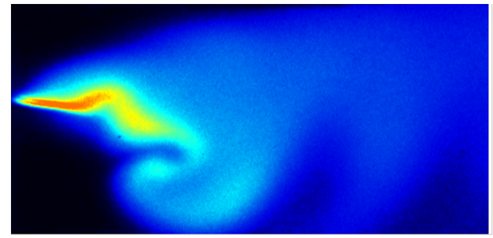
90° - 135°



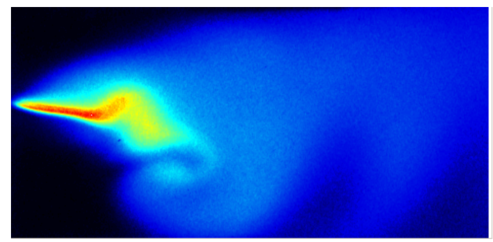
135° - 180°



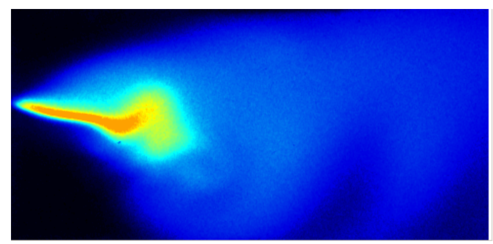
180° - 225°



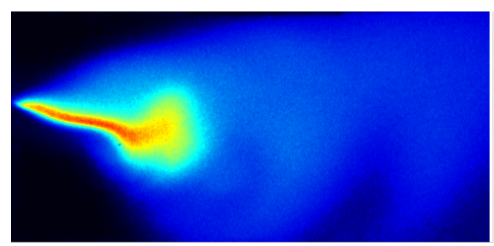
225° - 270°



270° - 315°



315° - 360°



Ditaranto & Hals / 2nd IEAGHG Oxy-Fuel Workshop, 2007

Conclusions

- Oxy-Fuel combustion systems offer more complex instability patterns than air supported combustion
- The increase in burner stability by oxygen enrichment can lead to an increase of dynamic instability
  - Staging of O_2 to enhance combustor performance should be done carefully
- Knowledge of flame properties in CO_2/O_2 systems is necessary to predict the flame structure

1st Young Researchers Forum

Developments in Oxy-Combustion Technology for Power Plant with CCS

by:

Stanley Santos

IEA Greenhouse Gas R&D Programme

Presented at:

TU Hamburg-Harburg

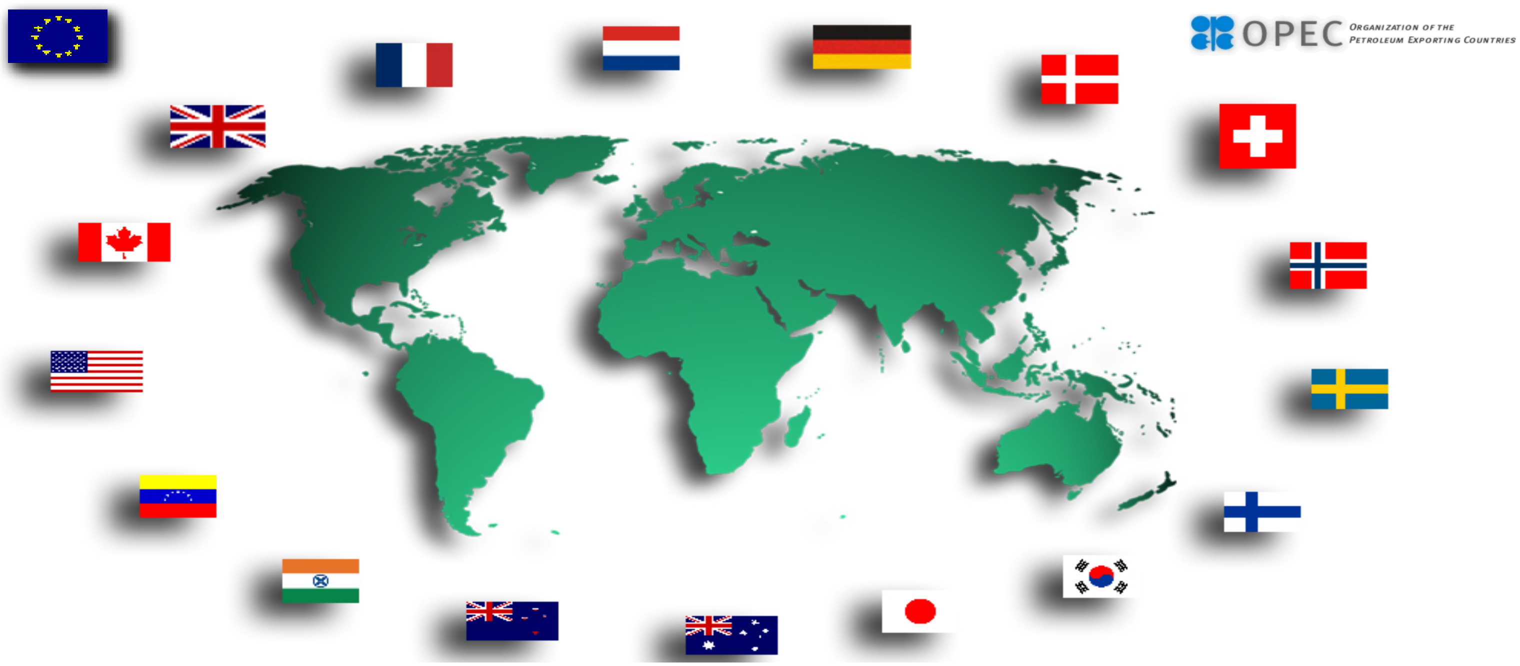
8th December 2006

***Corresponding Author's Email: stanley@ieaghg.org**

Introduction to IEAGHG

- IEA Greenhouse Gas R&D Programme (IEAGHG)
  - An organisation having an implementing agreement with the International Energy Agency.
  - A collaborative research programme that started in 1991.
  - A programme supported by 17 member countries, European Commission and 14 industrial sponsors
- Our main role is to evaluate (without any bias) technologies that could provide significant reduction to the greenhouse gas emissions.
- **Our main aim is to provide our members with an up to date information on the role that technology can play in reducing greenhouse gas emissions**

Programme Members



ALSTOM BG GROUP bp Chevron EniTecnologie e·on EPRI

ExxonMobil REPSOL YPF RWE STATOIL TOTAL VATTENFALL

What do we do?

- New phase (5) started at end of 2004:
  - 3 Main activities:
    - A1: Technology and Market information
    - A2: Confidence building
    - A3: Information dissemination
  - Aimed at answering:
    - How do options compare?
    - Can the option be done safely and legally?
    - What needs to be done to introduce the technology and be confident it will work?

Introduction to IEAGHG

- Accumulated > 100 studies in the past 15 years in operation. In the previous year, member's studies completed, include:
  - Environmental impact study on CO_2 Scrubbing
  - Factors in considering investment for carbon capture
  - Post combustion capture of CO_2 from power generation
  - Oxy-combustion for power generation and CO_2 capture
  - IGCC with CO_2 capture for power generation
  - Cost and capacity for CO_2 storage in Europe and N America
  - Monitoring requirements for CCS
  - Long term framework for CCS
  - Use of CDM for CCS
  - Carbon Capture Option for Low Rank Coal

Some of Upcoming Technical Studies

- Definition of Capture Ready Plant
  - Work done in conjunction with IEA under task requirement of Gleneagles G8 meeting

- Co-production of Hydrogen and Electricity

International Network

- Communication
- Provide the avenue for discussion and support any confidence building activities
- IEAGHG manages 6 Research Networks
  - International CO_2 Capture Network
  - International Oxy-Combustion Network
  - Biofixation Network
  - Monitoring Network
  - Risk Assessment Network
  - Well Bore Integrity Network

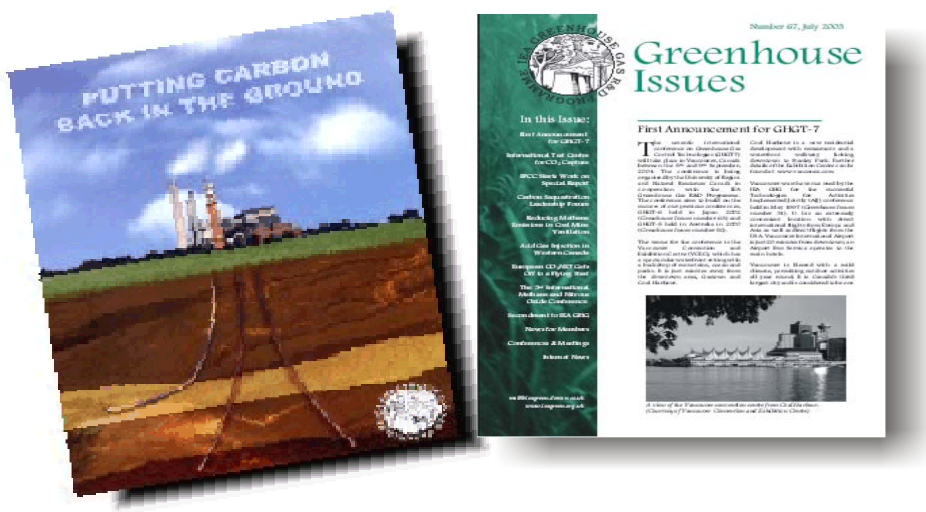
International Network Workshop Meeting

- International Oxy-Combustion Network
  - 24th – 26th January 2007
  - Windsor, CT, USA
  - Hosted by Alstom Power.
  - Now fully book – with 80 participants!
  - Session 7 includes a panel discussion among the 6 large scale demonstration oxy-combustion projects
- International CO_2 Capture Network
  - May 2007
  - Hosted by IFP
  - Paris, France

Communication & Information Dissemination

Quarterly newsletter

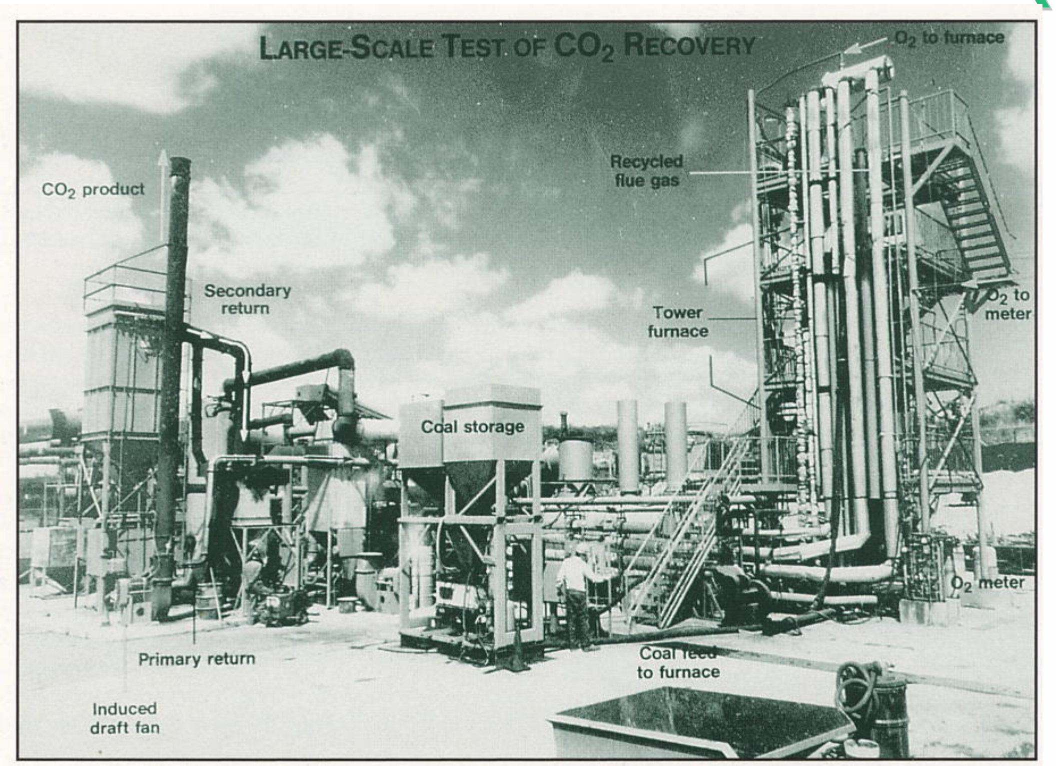
Topical Reports

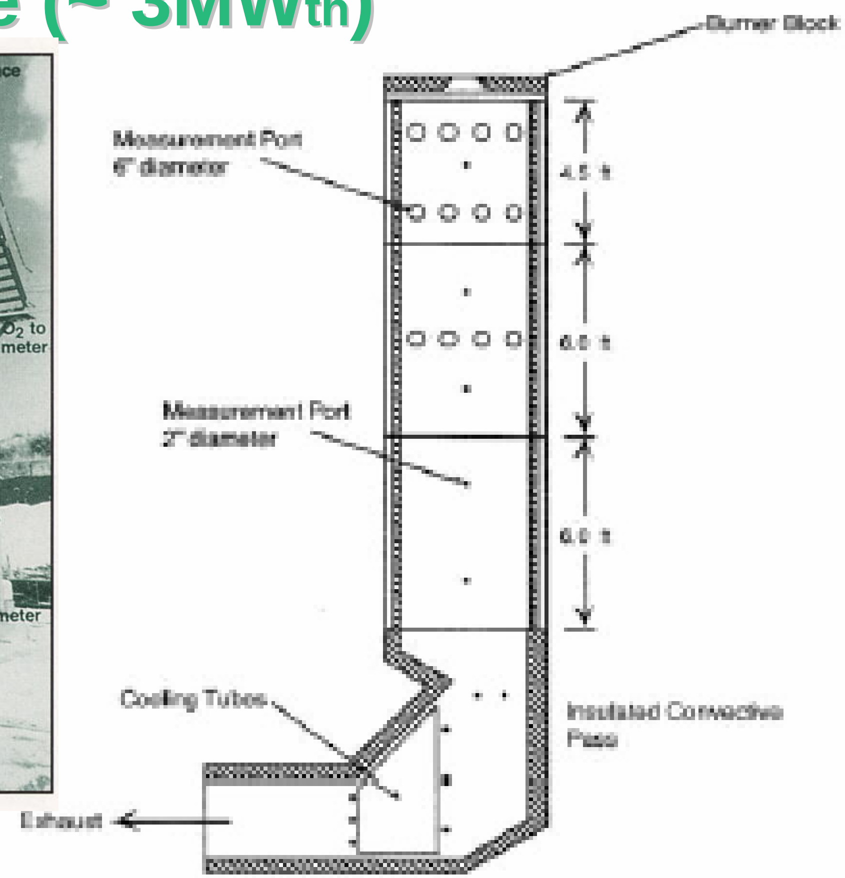


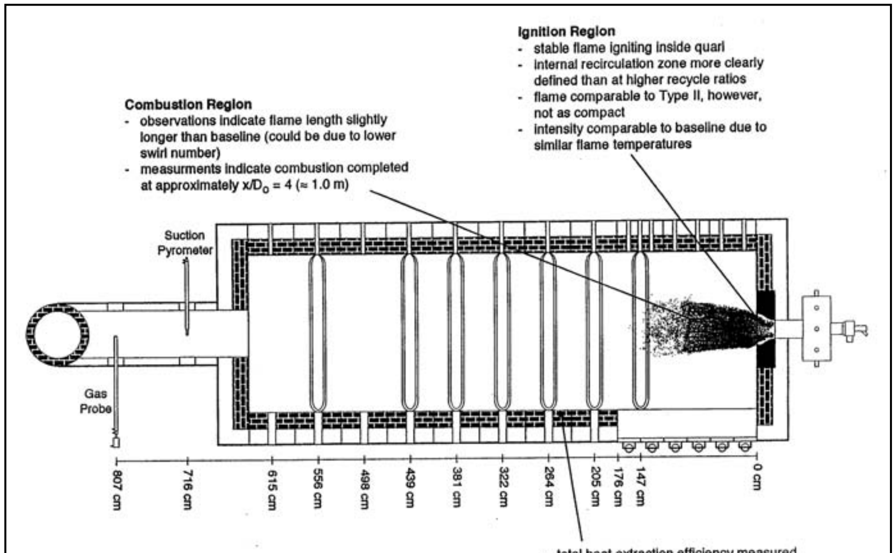
IEA Greenhouse Gas R&D Programme

R&D Update for Oxy-Coal Combustion Technology

ANL - EERC Study
World's 1st Oxy-Coal Pilot Scale Study
Tower Furnace (~ 3MWth)

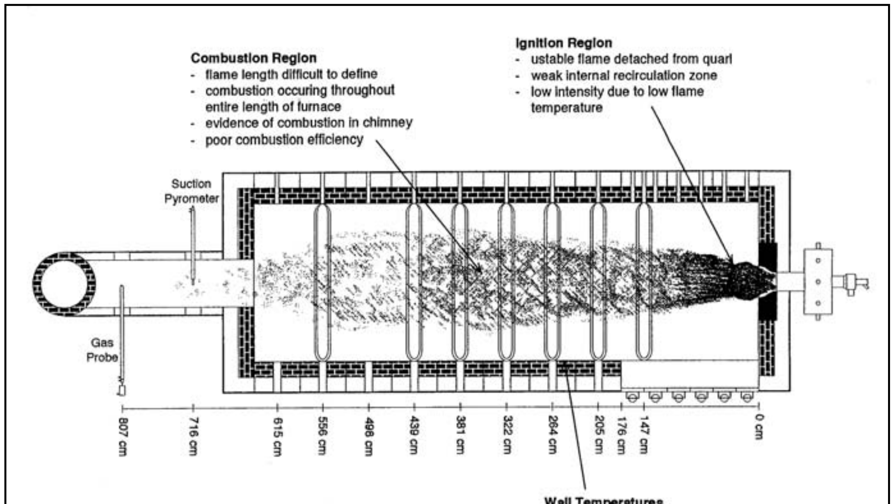






O_2-RFG flame with recycle ratio = 0.58

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

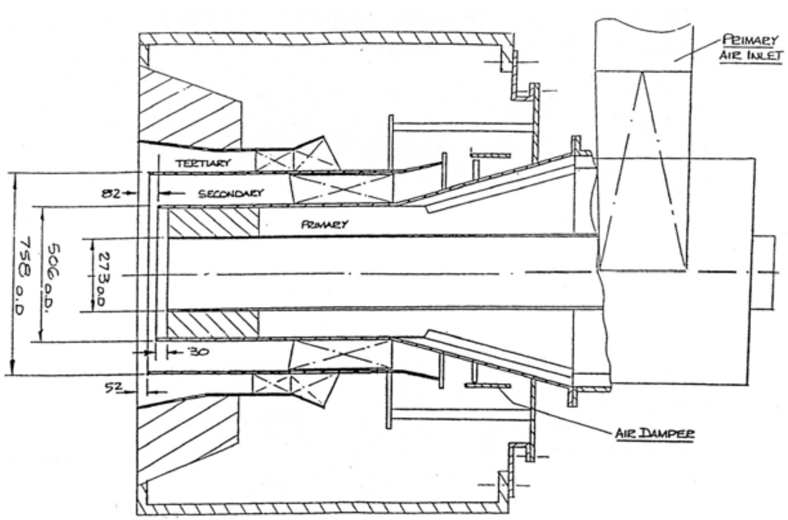


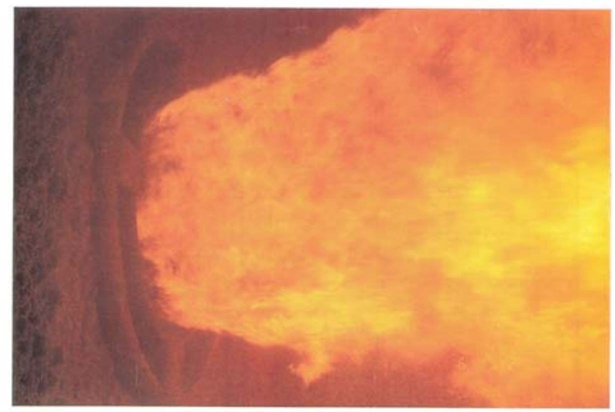
O_2-RFG flame with recycle ratio = 0.76

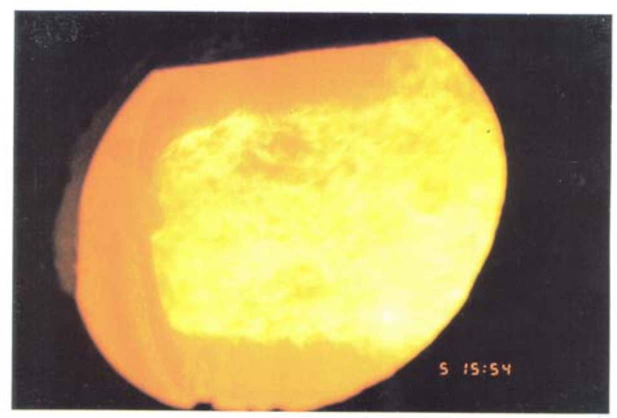
Recycle Ratio = 0.76

Courtesy of IFRF

1st Large Scale Oxy-Coal Combustion Experience (International Combustion Ltd.)



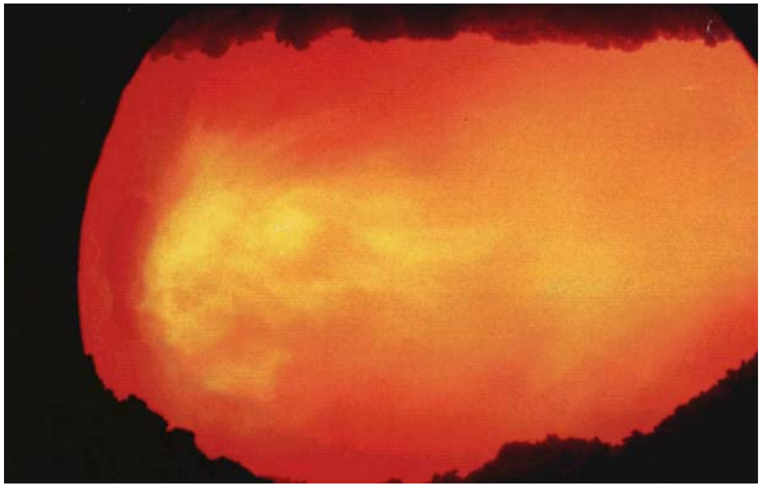




Test 3 - O_2/RFG Firing

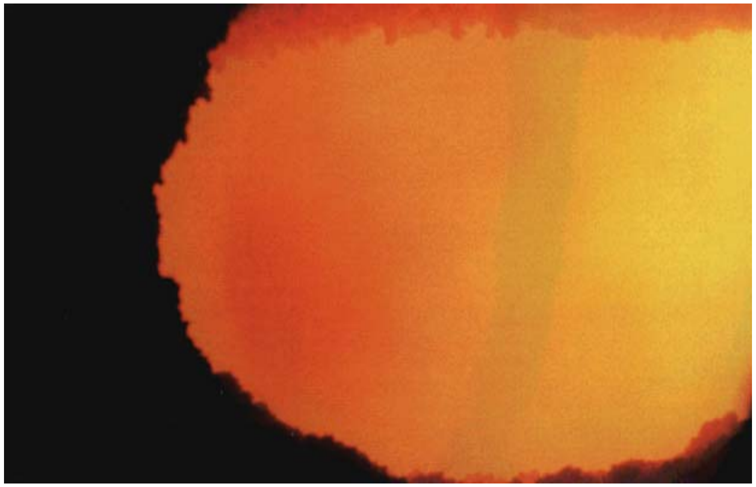
- ✓ 35 MWth Low NOx burner
- ✓ Although it was not able to achieve the desirable CO_2 composition – the first combustion trial gained significant experience in burner start up

Coal Flame Photos: Air Fired vs Oxy-Fired (Courtesy of IHI)



Air mode (O_2 : 21%)

Oxy mode (O_2 : 21%)

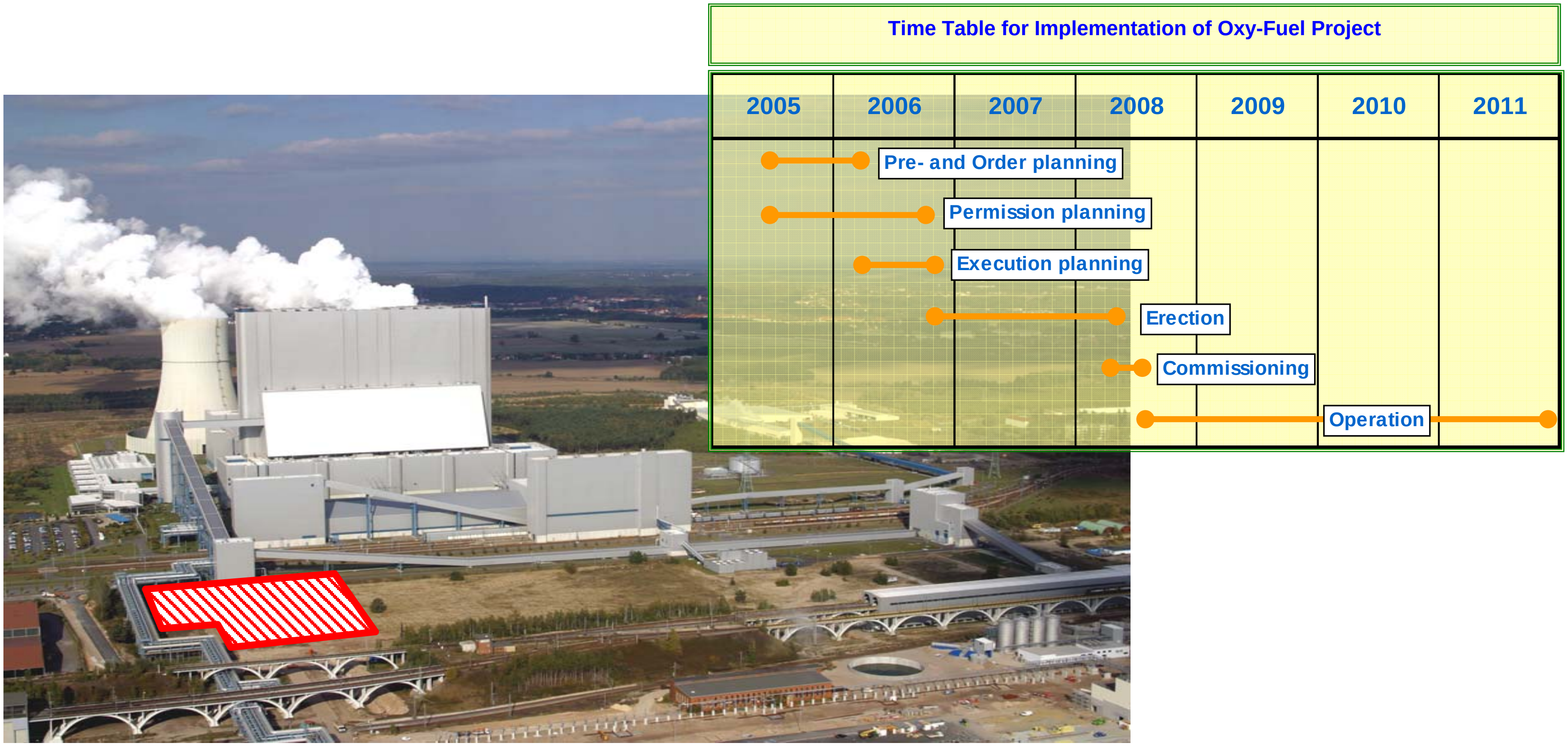


Oxy mode (O_2 : 30%)

Oxy-Combustion Technology

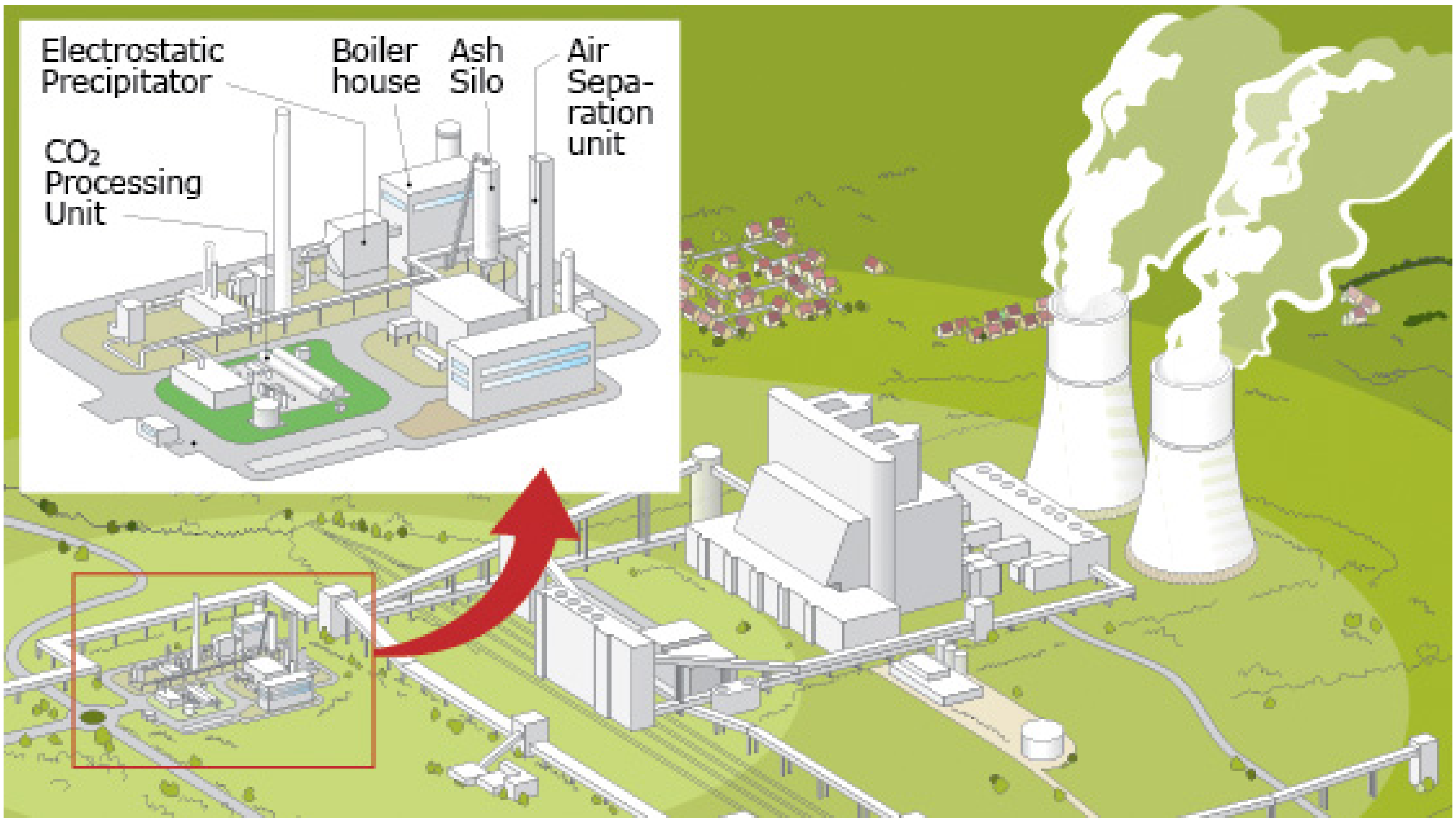
What are the different milestone that could provide a big step forward for Oxy-Coal Combustion…

R&D Effort in Europe



Courtesy of Vattenfall

Artist's View



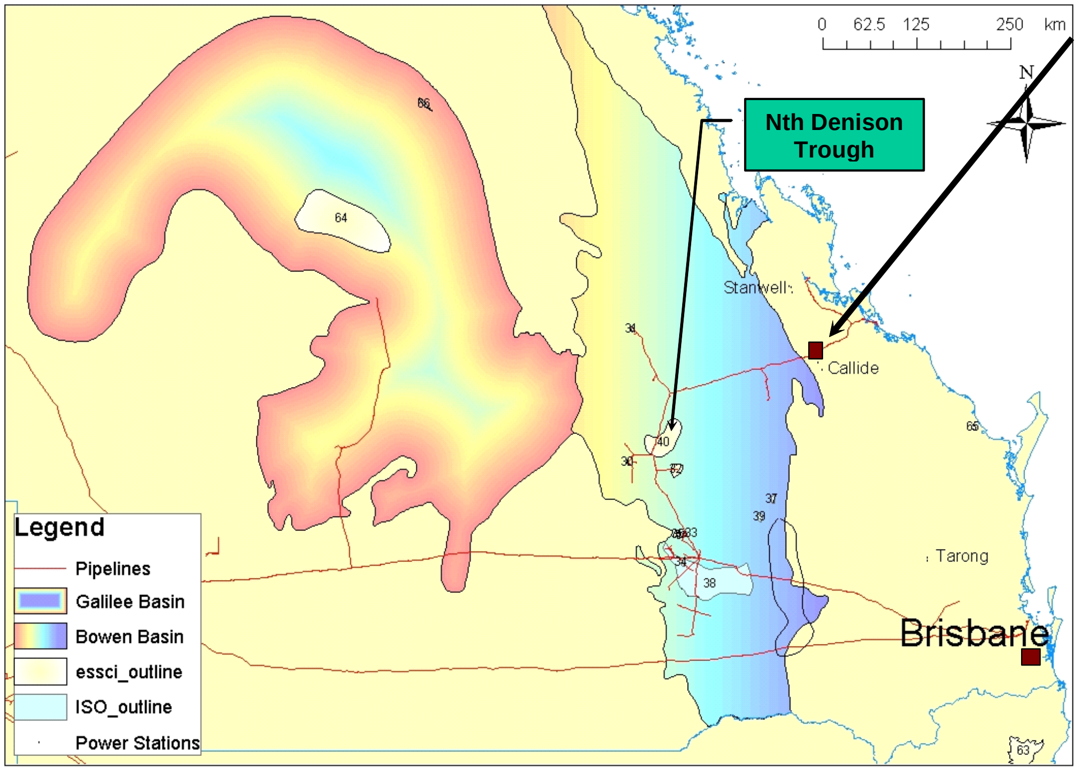
Japanese and Australian Co-operation

- Callide-A Oxy-Combustion Retrofit Project
- IHI (Japan) and CS Energy (Australia)

- 30th October 2006 – Australian Government announcing the $50 million grant from LETDF

- Project is also supported by the Australia Coal Association, JCoal, JPower (EPDC)

Callide A Project:
Japanese-Australian Collaboration



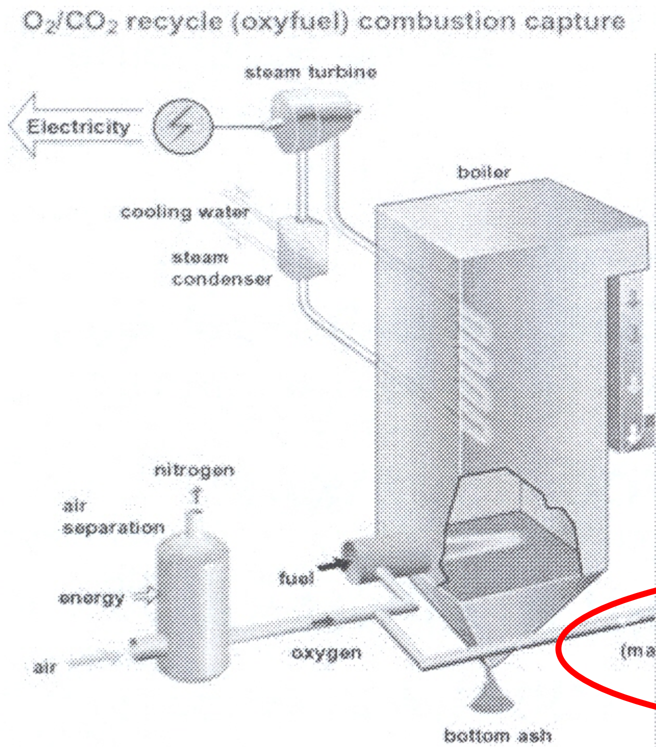
Callide-A Power Station

Capacity: 4 x 30 MW_e
Commissioned: 1965 – 1969
Refurbished: 1997/98

Steam Parameters: 4.1 MPa, 460°C
Steam Flowrate: 123 t/h steam

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

R&D Effort in Europe



- Pilot scale tests by Mitsui Babcock 1994
- IEA, EU projects underway
- EON 1MW rig recently announced
- Vattenfall 30MW demonstration plant announced
- Several boilermakers developing this technology for 2010/12 implementation
- Full scale 60MW burner test planned by MBEL in 2007/8
- DTI funded collaborative R&D projects in preparation

MitsuiBabcock

Other Major Large Scale Oxy-Coal Combustion Projects

- 30th October 2006 Announcement: SaskPower (Canadian) choosing Oxy-Combustion for their 300MWe Clean Coal Project (in co-operation with Babcock and Wilcox and Air Liquide)
- Jupiter Oxygen (USA) – 26MWe Retrofit Project – in co-operation with NETL, Ohio Air Quality Development Authority and Orville Utilities.

Forum Vision

A workshop for you to meet other colleagues who are also working in Oxy-Combustion Field…

– Updated Version –

1st Young Researcher Forum
TU Hamburg-Harburg
8th December 2006

Combustion Tests and Modeling of the Oxy-Fuel Process An Overview of Research Activities at Chalmers University

KLAS ANDERSSON

Department of Energy and Environment
Chalmers University of Technology

(Also presented at the 2nd Oxy-Combustion Workshop at Windsor, CT, USA on 25/01/2007)

The oxy-fuel group at Chalmers consists of 7 researchers at the dept. of Energy and Environment:

- Prof. Filip Johnsson
- Prof. Bo Leckner
- Associate Prof. Henrik Thunman
- PhD cand. Stefan Hjärtstam (CFD modelling & experiments)
- PhD cand. Robert Johansson (Heat transfer modelling)
- PhD cand. Fredrik Normann (Chemistry modelling)
- PhD cand. Klas Andersson (Experiments and heat transfer modelling)

Experimental and combustion modeling work performed in various projects

- Close collaboration with Vattenfall, FLUENT and IVD/Uni-Stuttgart, AGA/Linde and DOOSAN/Mitsui Babcock etc.

The focus of the Chalmers group is on the combustion fundamentals of the process – for gas and coal-firing so far

- Combustion chemistry
- Heat transfer
- Fluid mechanics

- Both gas- and coal-fired experiments required in CFD model development – SCALING
- The combustion tests comprise:

→ **Propane fired tests:** to identify and characterize **differences in flame properties** between oxy-fuel and air combustion conditions

→ Emphasize put on the difference in radiation characteristics, without the influence from particles and ash

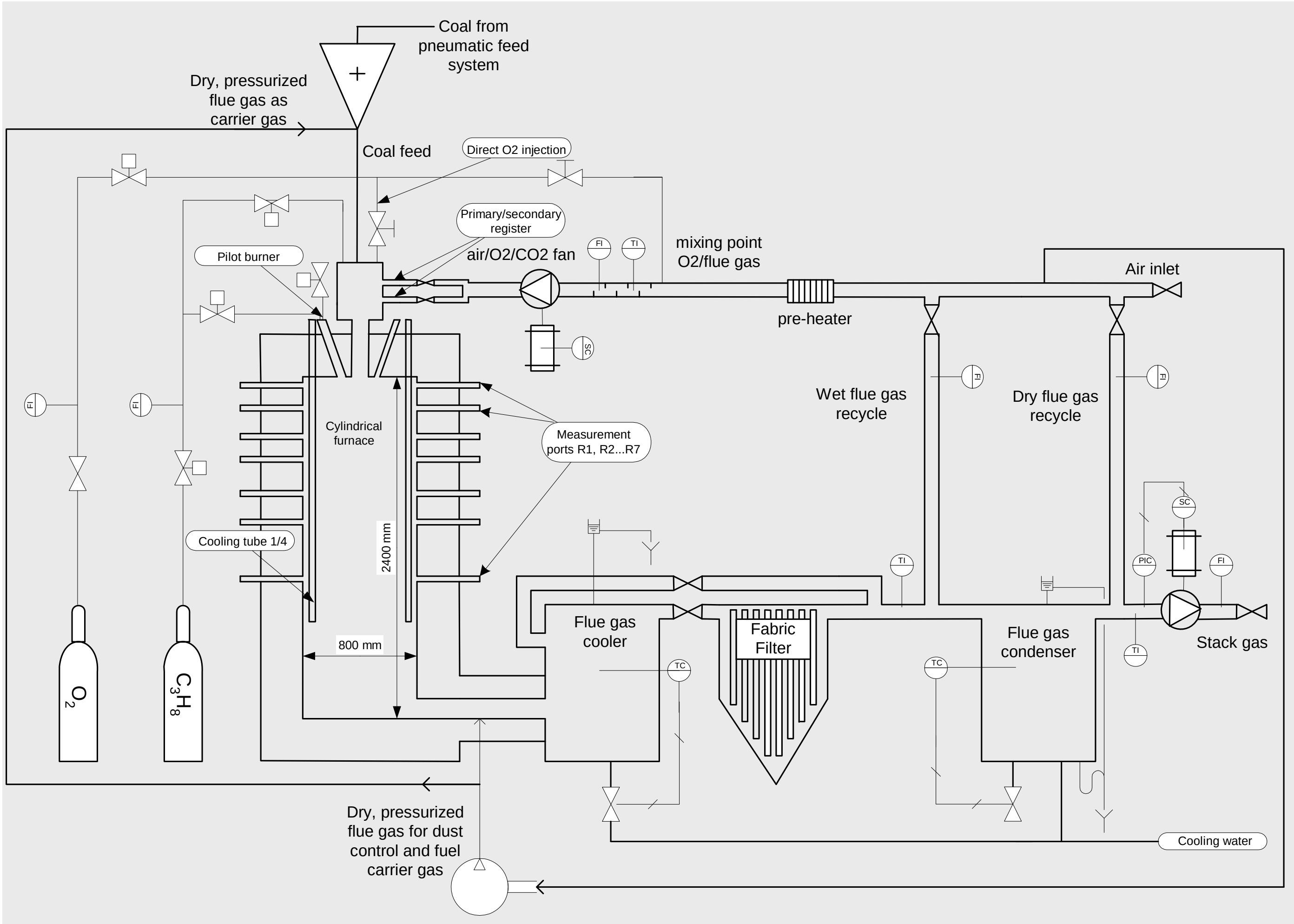
→ **Lignite fired tests:** to evaluate the combustion fundamentals of lignite-fired flames in air and various O_2/CO_2 environments

→ Focus on combustion chemistry and transfer/radiation

CHALMERS 100 kW_{th} oxy-fuel test facility

100 kW_{th} test unit
- -Gas-firing
- -Coal-firing
- -Oxygen enriched combustion (separate lance)

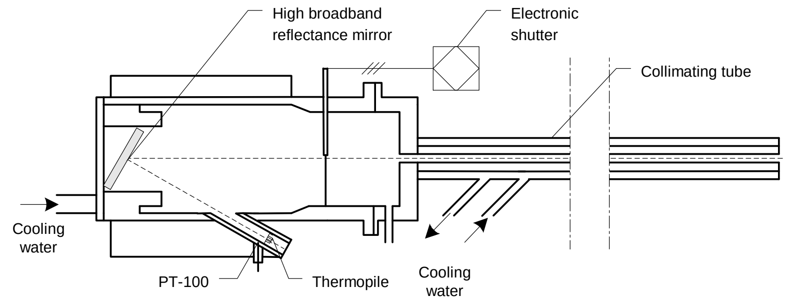
Combustor:
- Di = 0.8m
- H = 2.4 m
- Refractory lined
- 7 x 4 meas ports
- optical access



RESULTS FROM GAS-FIRED TESTS

Test conditions and measurements during Gas-fired tests

- **In-furnace measurents:**
  - gas composition
  - Temperature
  - Radiation intensity profiles
  - Velocity profiles (@STP)



Fuel input	80 kWth	Fuel		C_3H_8	Stoich ratio		1.15
Primary register	Fin angle	Swirl No		Secondary register	Fin angle		Swirl No
	45	0.79			15		0.21
Test case	Combustion media	Temp feed gas [°C]	Feed gas composition (vol %)				Theoretic CO_2 conc. @ stack (vol %)
			O_2	N_2	CO_2		
Air	air	25-30	21	79	-		12
OF21	O2/CO2 dry recycle	25-30	21	-	79		97
OF27	O2/CO2 dry recycle	25-30	27	-	73		96

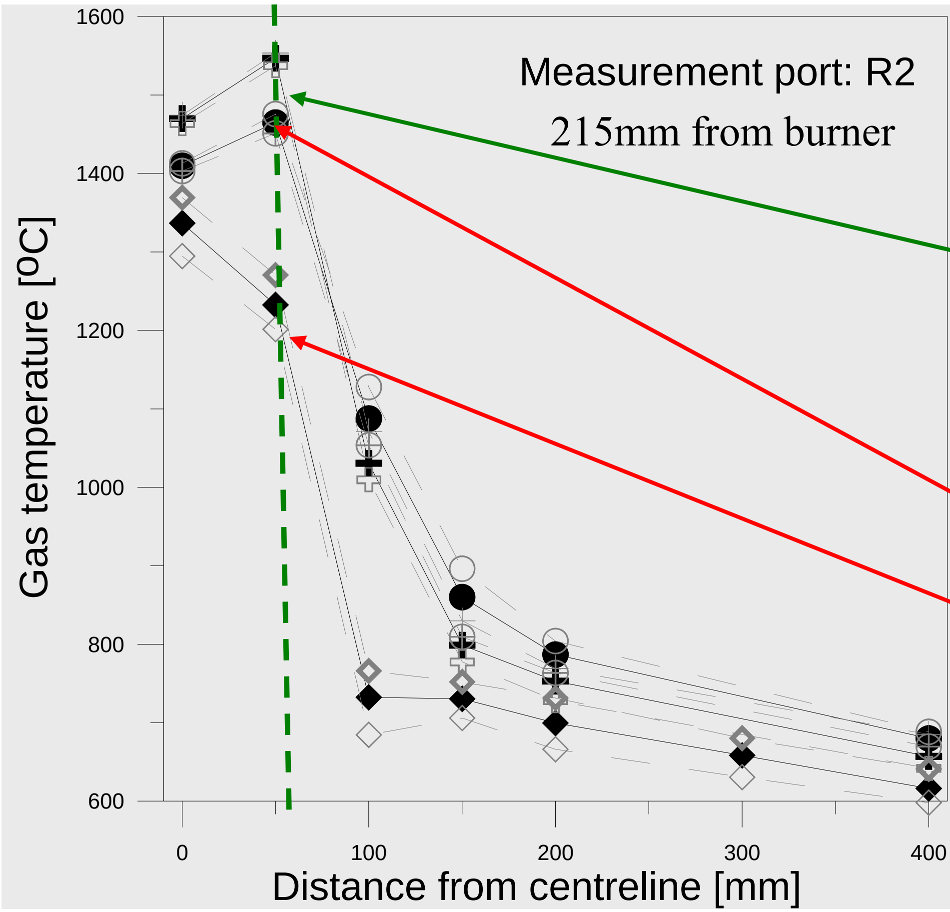
Flame emission from propane-flames, 215 mm from burner inlet

- **The flame emission changes significantly for different oxy-fuel conditions**
- **This effect is caused by different rates of soot formation, which is affected by the CO_2 (and recycle rate) through the following mechanisms**

  - Thermal effects (soot formation is dependant on temperature)
  - Chemical effects from CO_2 (The CO oxidize soot-precursors)
  - Dispersion (The conc. of soot precursors, e.g. acethylene, vary with RR)

Air-firing, $\lambda = 1.15$ Oxy-fuel, OF 21, $\lambda = 1.15$ Oxy-fuel, OF 35, $\lambda = 1.40$

Radial temperature profiles: 215 mm from burner inlet

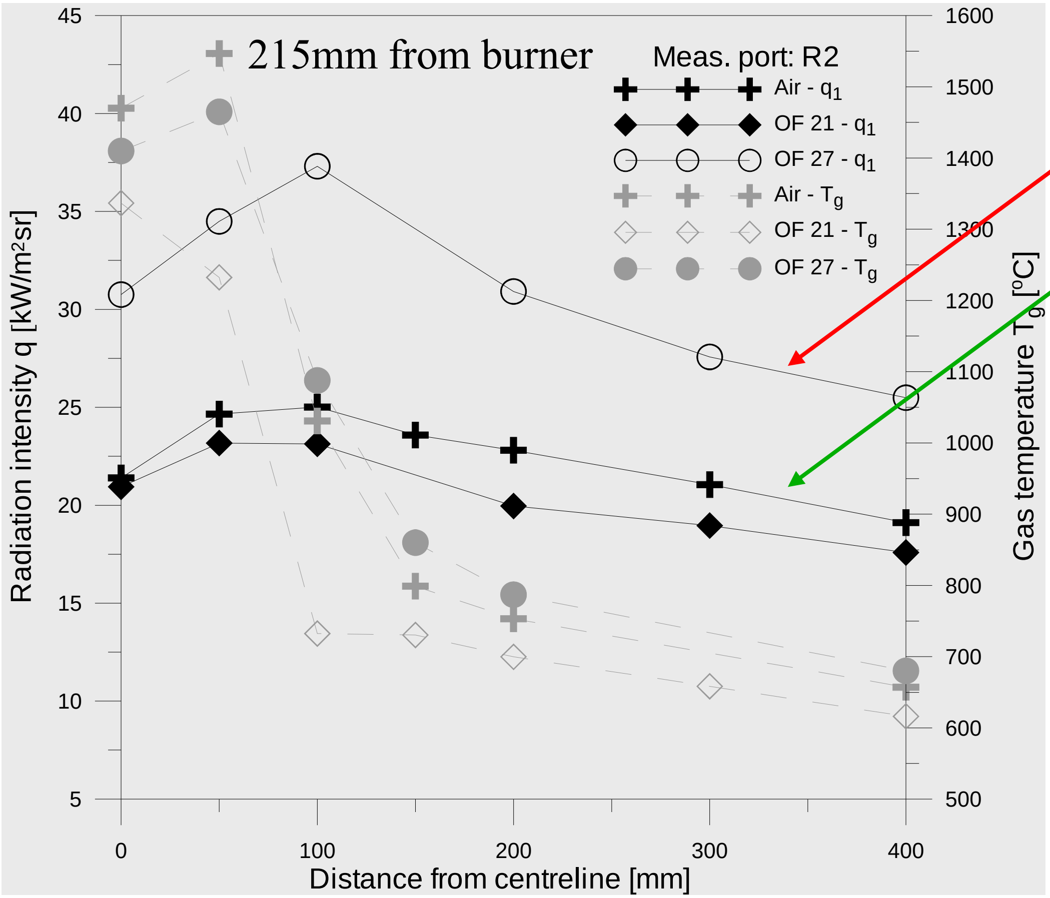


- Profile: centre line to furnace wall
- Reaction zone
- Oxyfuel combustion: temperature control by flue gas recycle rate:

● OF27

❑OF 21

Radial temperature and radiance profiles



- OF 27 case similar temperature levels as for air. Radiation intensity from the flame increases 20-30%.
- Change in emissivity
  - Gas radiation
  - Soot radiation

Gas emissivity

Air case: $\varepsilon_g = 0.23$

OF 27 case: $\varepsilon_g = 0.29$

Mean Radiation Temperature

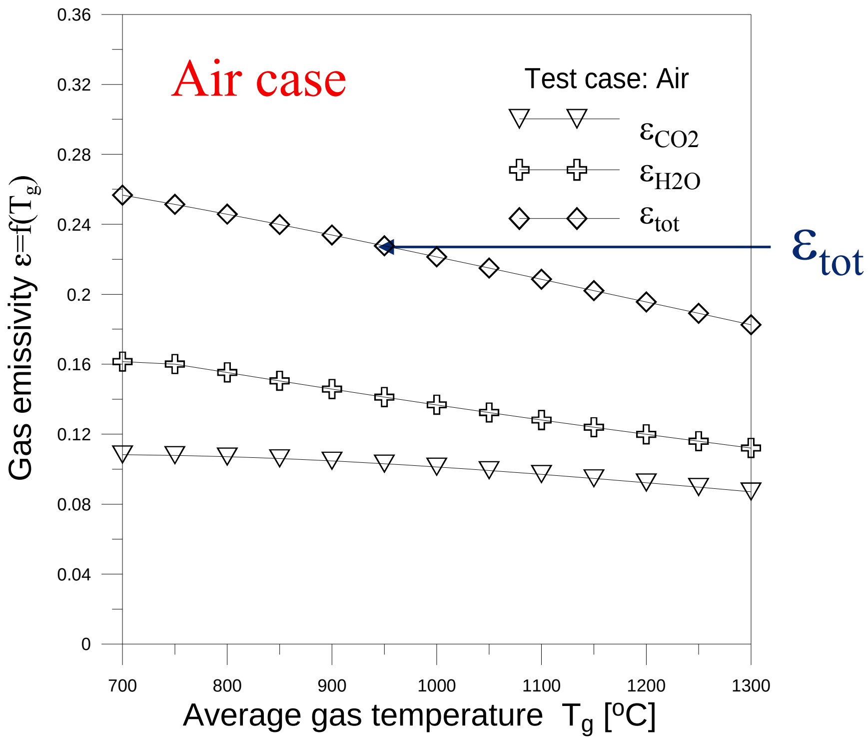
$T_{mr} = 930^oC$

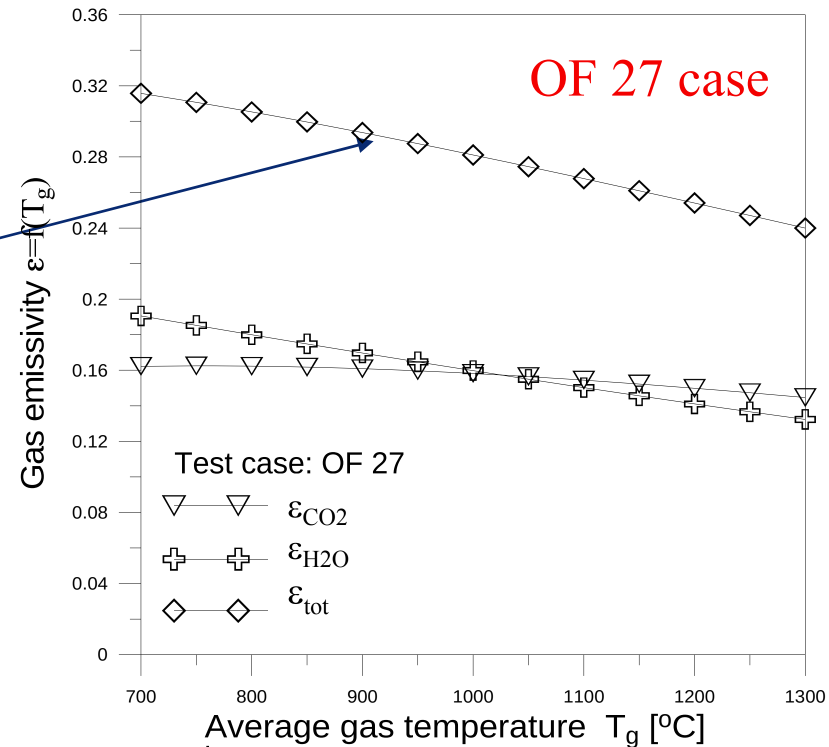
$T_{mr} = 950^oC$

Mean emissivity

Air case: $\varepsilon_m = 0.40$

OF 27 case: $\varepsilon_m = 0.52$





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

Summing up

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 performance/burn-out behavior
- The radiation intensity of the OF 27 flame increases with about 20-30% despite similar temperature profiles as in air case
- Increased emissivity in the OF 27 case is both due to increased gas band radiation as well as an increased soot volume fraction

RESULTS FROM LIGNITE-FIRED TESTS

Test conditions Chalmers 100 kW test unit

Total operation time on lignite: ~1000 h

- With oxy-fuel conditions: ~300 h
- Total measurement time: ~220 h

Same overall stoichiometry for all test cases: λ = 1.17

Oxy-fuel test conditions:

OF 27: 27% O_2 and 71.5% CO_2 (RR = 0.77)

- OF 27 for coal compares rather well to OF 27 for gas.
  - combustion temperatures and flame stability are similar
  - Slightly higher flame temperatures than for air

OF 25 (RR = 0.79) and OF 29 (RR = 0.75)

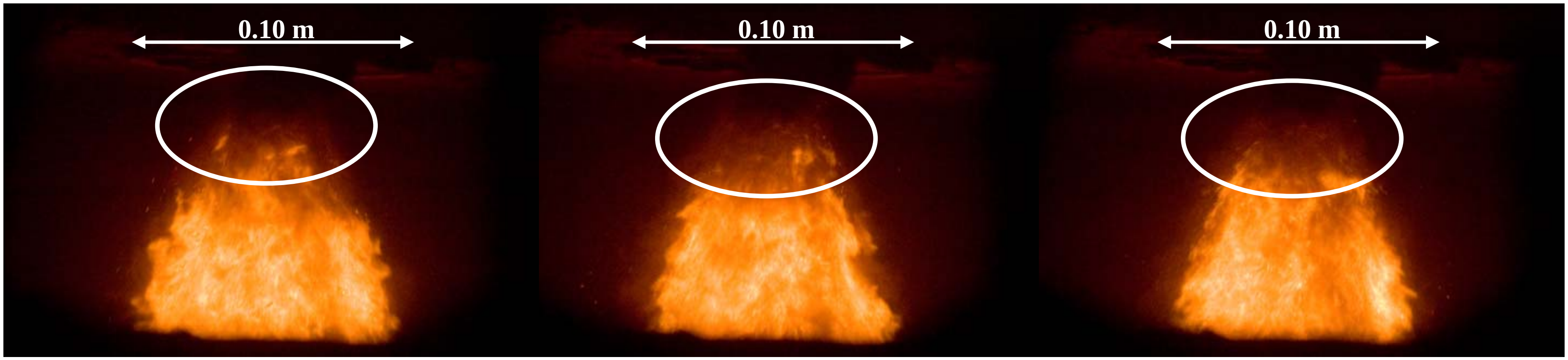
- Temperatures around ash melting point achieved already for OF 29 (around 1350 C)
- OF 25 results in rather similar temperatures in the flame zone

Measurements performed at Chalmers

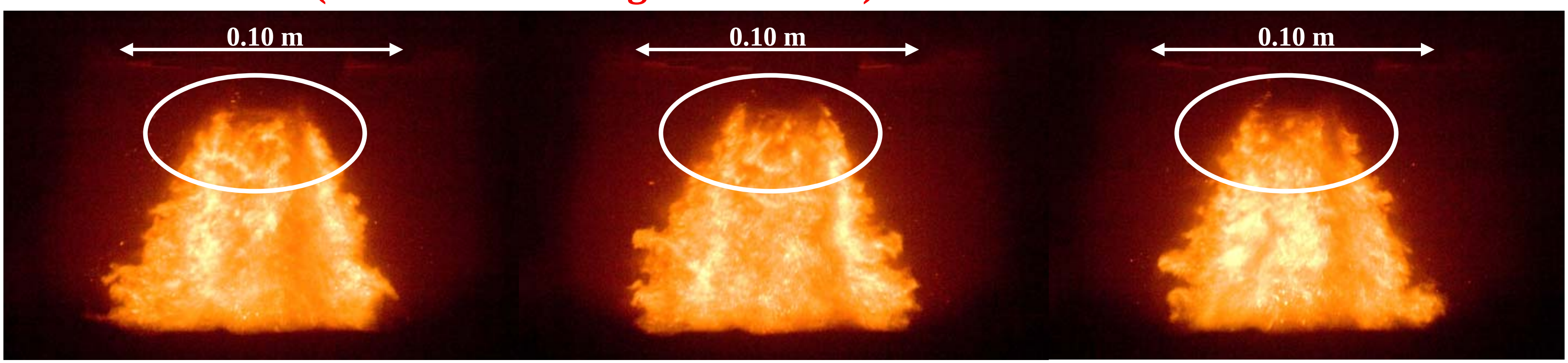
- Gas concentration profiles
  - O_2, CO, HC, CO_2, NO_x, SO_x
  - suction probe/online gas analysis
  - SO_3 measurements
- Temperature profiles
  - suction pyrometer (thermocouple type B, 2000K)
- Radiation Intensity profiles
  - Narrow angle radiometer (IFRF type)
- Particle mass concentration profiles
  - Isokinetic sampling probe
- Burn-out profiles (isokin. samp.)

Flame emission from lignite-fired flames in air and OF 27 environments - Pictures taken @ burner inlet

Air-fired flame: λ = 1.17 (O_2 excess in flue gas: 3.0 vol%)

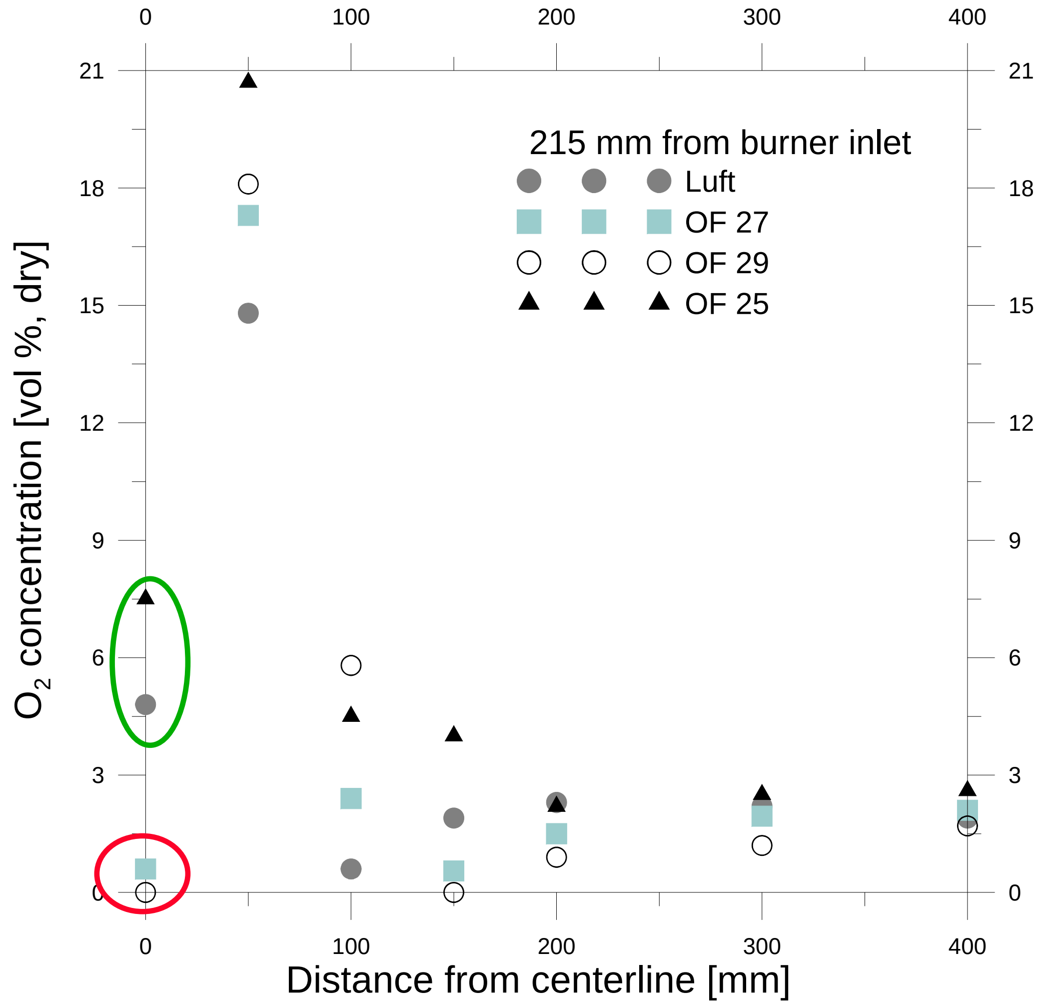


OF 27: λ = 1.17 (O2 excess in flue gas: 4.0 vol%)



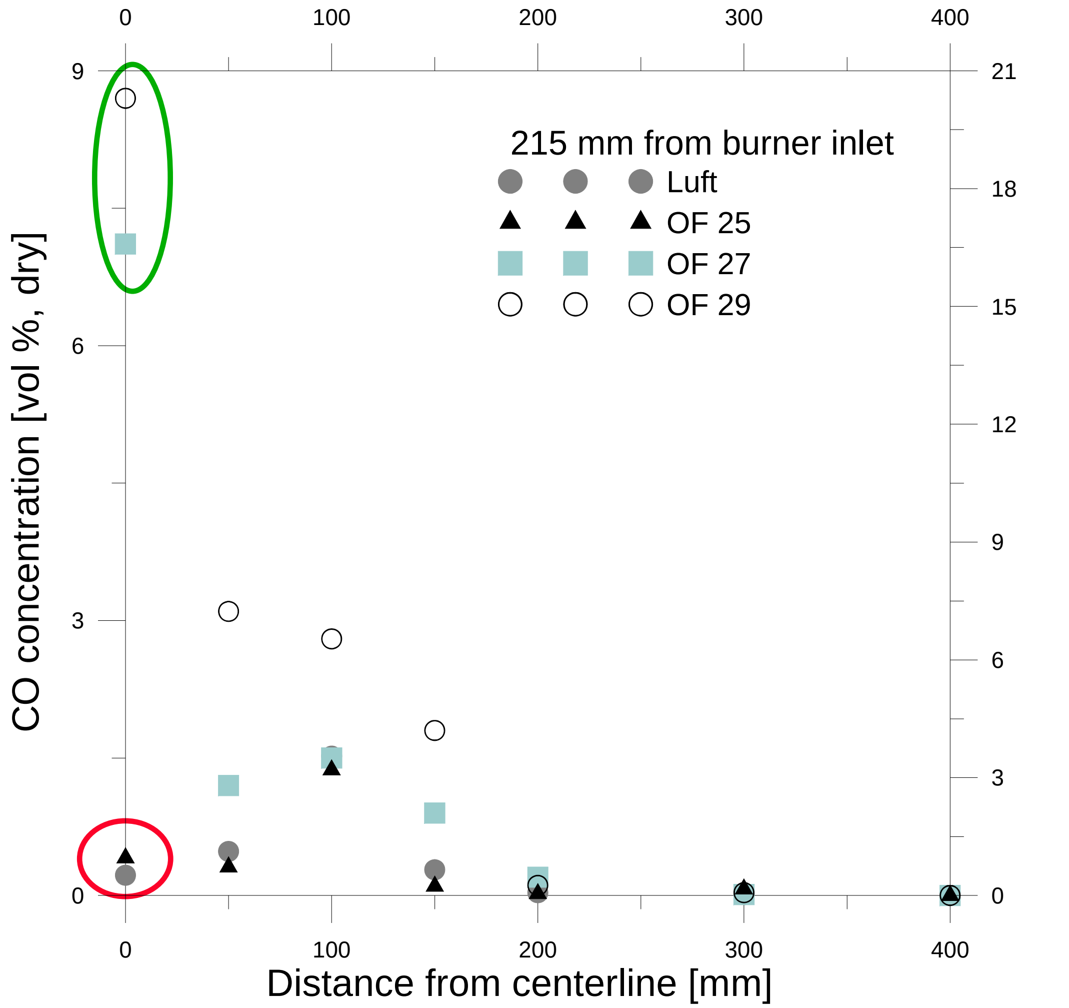
O_2 profiles, 215 mm from burner inlet

- Difference in ignition can be detected from O_2-profile measurements
- Oxygen consumed faster in OF 27 and OF 29 flames compared to OF 25 and air-fired conditions.



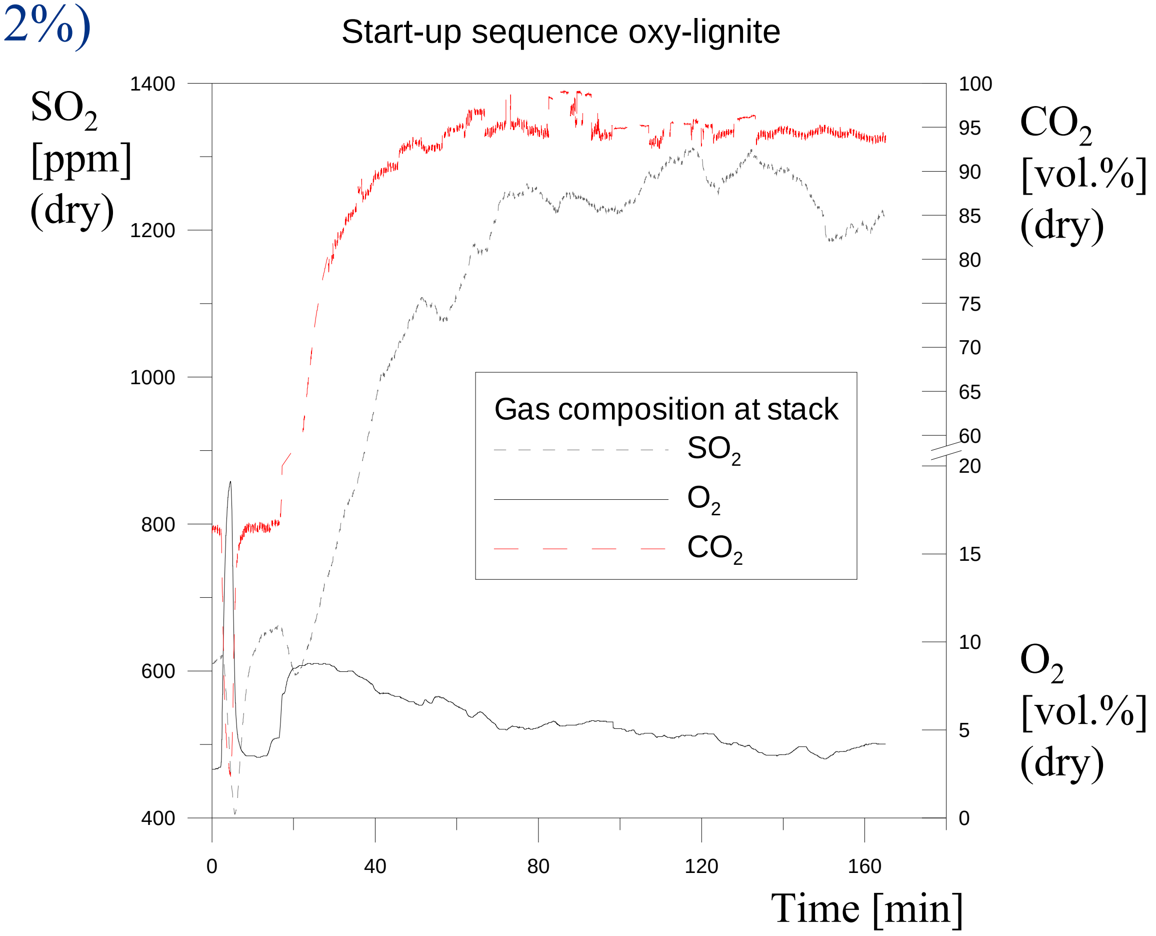
CO profiles, 215 mm from burner inlet

- And marked differences can also be detected from the CO-profiles
- High centreline CO concetrations for OF 27/OF 29
- Little CO formation in air/OF 25 flames on centreline



Start-up sequence from air to OF 27 conditions

- O_2, CO_2, SO_2 before condenser
- Total concentration level about 98-98.5%, i.e. very low leakage levels (below 0.2%)
- Stable $CO_2/SO_2/O_2$ Levels after 120-160 min
- Feed gas composition as measured: 26.9 vol% O_2 72.3 vol% CO_2 (discrepancy due to N_2)



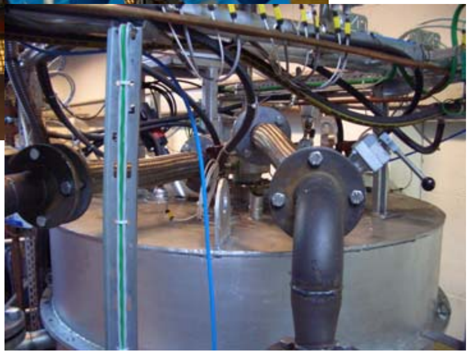
Emission concentrations measured at combustor outlet

->Negligeble differences in CO emissions between different cases

->SO_2 and NO_x accumulated in the recycle loop, but emission rates [mg/MJ] significantly lower than for air

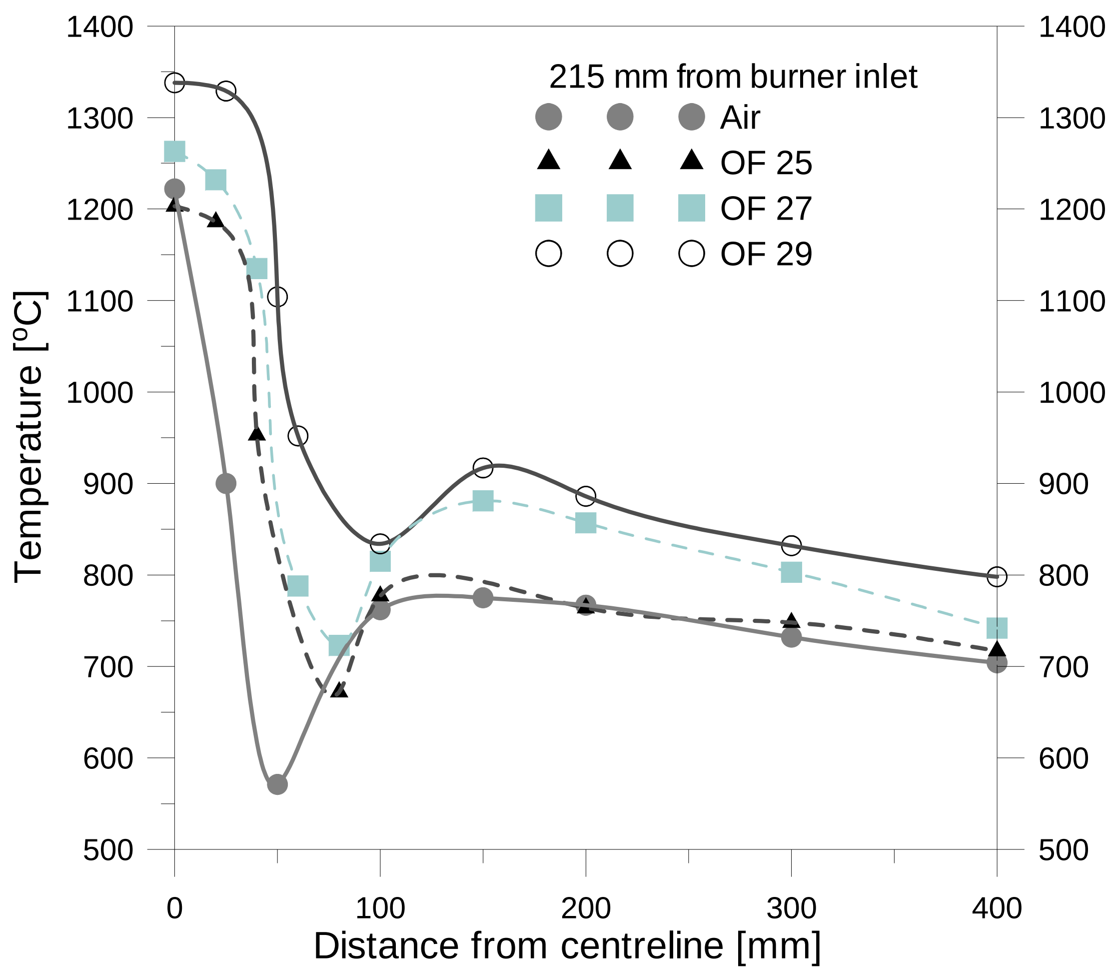
-> SO_2 level reduced to about 40%
-> NO_x level reduced to less than 30 %

	CO [ppm]	NO_x [mg/MJ]	SO_2 [mg/MJ]
Air	130	233	510
OF 25	210	56	181
OF 27	170	62	187
OF 29	150	65	199



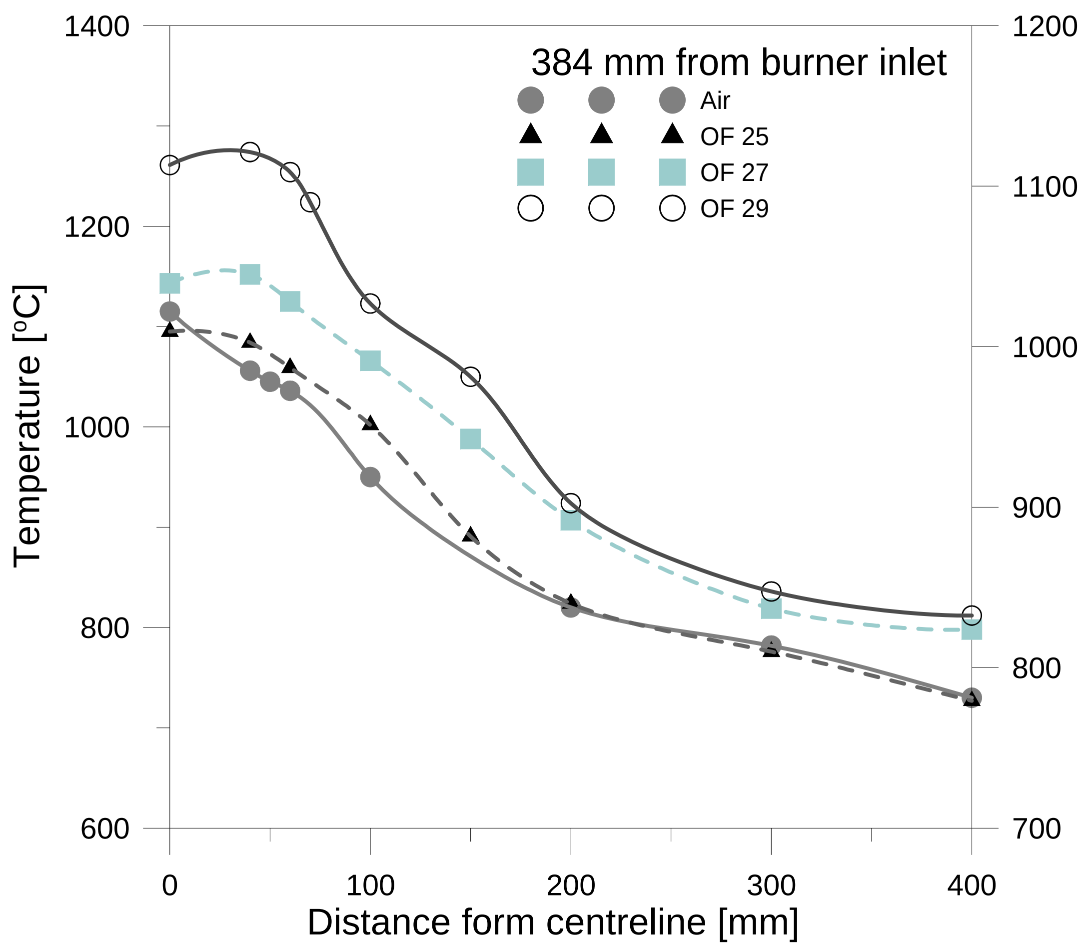
Temperature measurements 215 mm from burner inlet

- Oxy-fuel temperatures increase smoothly with decreasing recycle rate with highest temps for OF 29
- Inlet velocities increase with higher recycle rate
- Impulse from primary stream stronger for OF 25/Air than OF 29.



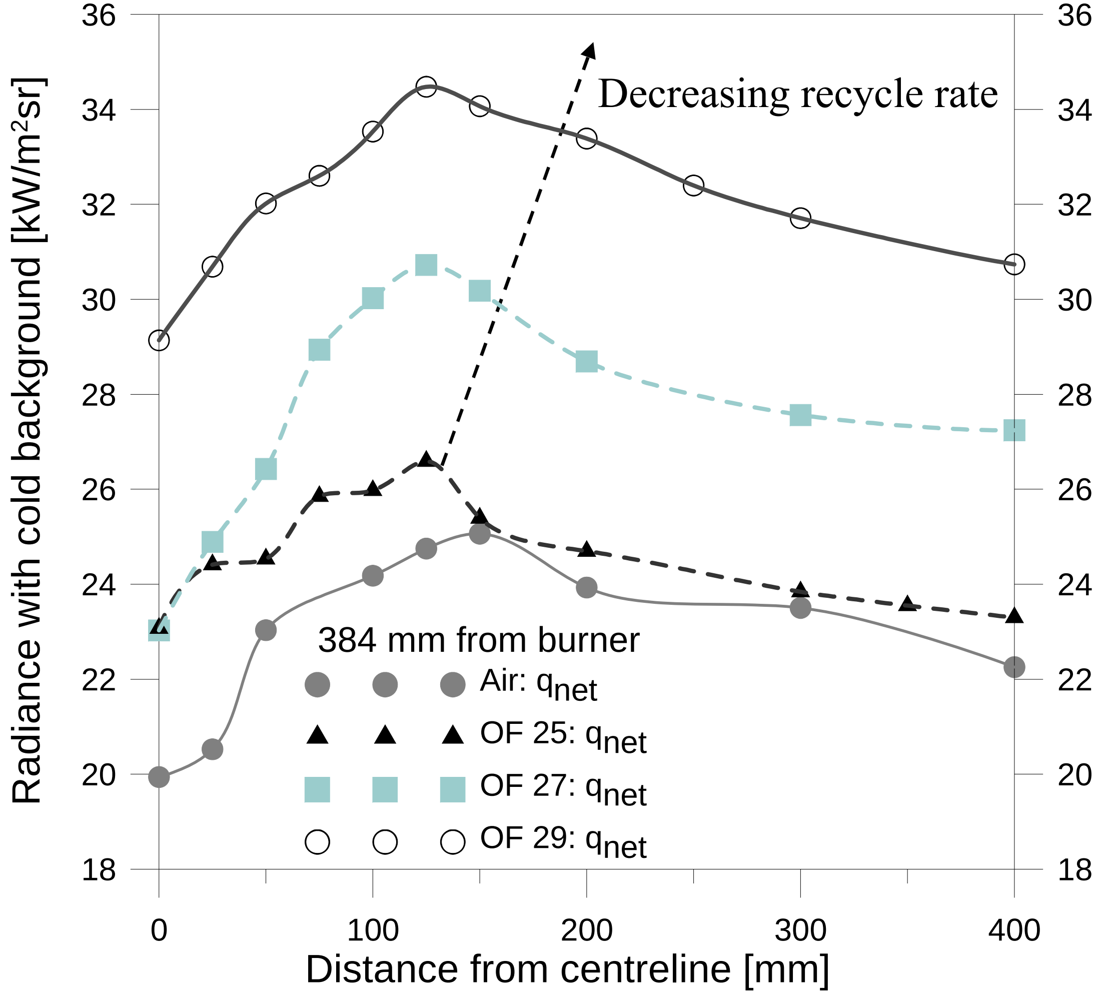
Temperature measurements 384 mm from burner inlet

- Temperatures for Air and OF 25 similar at most flame positions



Radiance measurements 384 mm from burner inlet

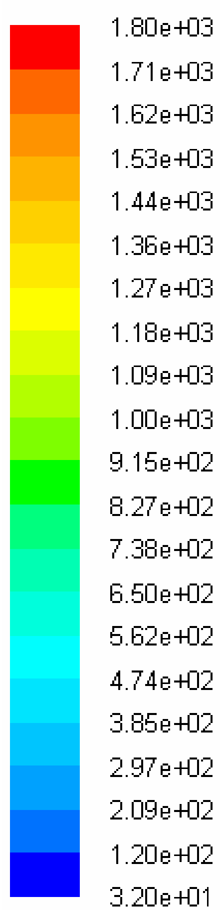
- Radiation intensities similar for Air and OF 25 – in analogue with the measured temperatures.
- Radiation increases with decreasing recycle rate.
- Particle radiation completely dominates radiation in both air-fired and oxy-fired environments.



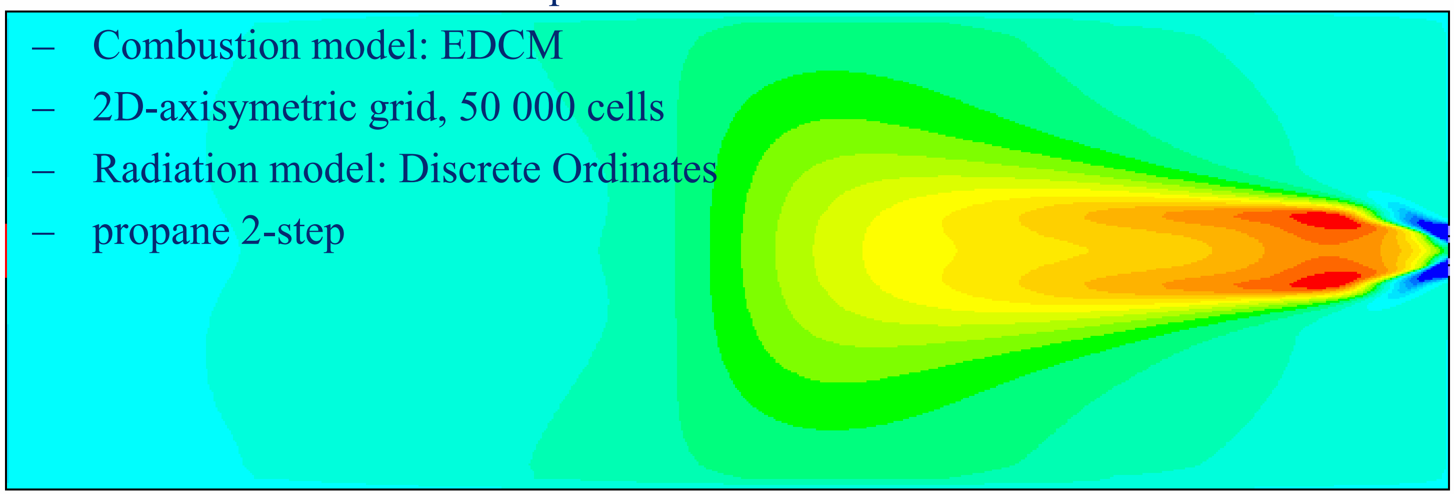
CFD-modeling of the 100 kW combustor

Important tool in the scaling from semi-industrial to pilot to demo

– Evaluation of the various sub-models (here FLUENT) for



- Gas phase reactions
- Radiative heat transfer
- Soot formation and destruction
- Results from propane-fired flame: temperature contours
  - Turbulence model: Std k-eps
  - Combustion model: EDCM
  - 2D-axisymetric grid, 50 000 cells
  - Radiation model: Discrete Ordinates
  - propane 2-step



Radiation modelling

- Using the radiation data from the gas-fired flame
  - Down stream of flame with near pure gas radiation: EWBM and WSGGM models tested against data
  - Choose gas radiation model
  - In-flame positions modeled to obtain soot volume fractions/absorption coefficients
  - Evaluate performance of soot formation models in CFD tool (FLUENT)
- Using the radiation data from the coal-fired fame
  - Add particle radiation model to evaluate the lignite-fired data
  - Model will be a valuable tool in the evaluation of the radiance measurements in the Schwarze Pumpe Pilot

Nitrogen and sulphur chemistry

- Nitrogen chemistry
  - Special designed experiments have been carried out for N-chemistry modeling purposes
  - Sensitivity of NO formation to air ingress and stoichiometry
  - Fuel-N formation and recycled NO destruction need further clarification
- Sulphur chemistry
  - It would be nice to close the mass balance!
  - SO_3 formation
  - Ash retention

Industrial scale oxyfuel combustion - outlook for pilot testing

- Scale up of experiments – 30 MW_{th} pilot plant
  - From mid 2008: Participation in pilot plant testing
  - Combustion research carried out by IVD, Chalmers and the other industrial partners involved
  - Use gained knowledge from 20/100/500 kW_{th} units
    - Establishment of test conditions
    - Expected overall combustion behaviour
    - Combustion modeling tools
  - Revisit smaller scale tests from issues arising in 30 MW pilot

Imperial College London

Overview of Oxyfuel (and some other CO_2 Capture) Research Activities

within the Energy Technology for Sustainable Development Group, Department of Mechanical Engineering, Imperial College London

Hannah Chalmers, Mathieu Lucquiaud,
Jon Gibbins (and a few others)

hannah.chalmers@imperial.ac.uk
m.lucquiaud@imperial.ac.uk

Overview

- CCS research at Imperial College London
- Some key projects and collaborations
- Summary of oxyfuel research activities
  - Combustion: experimental work on ignition (CFD soon)
  - System configuration options
  - Integration opportunities
  - Reliability, availability, maintainability and operability (RAMO)
- Brief overview of some other CO_2 capture activities

CCS research at Imperial College London

- Mechanical Engineering
  - Mostly our group…
  - …but some work elsewhere on chemical looping combustion and use of H_2 in gas turbine and fuel cells
- Chemical Engineering
  - Physical and chemical solvents and process modelling and optimisation
- Geology and Earth Science Engineering
  - Oil reservoir simulation and storage in coal beds

Some key projects and collaborations

- UK Carbon Capture and Storage Consortium (www.ukccsc.co.uk)
  - Project management of £2million, 3-year project with 14 UK academic institutions – funded by UK Research Councils in TSEC programme
  - Also, heavily involved with CO_2 capture work programmes
- IEA Greenhouse Gas R&D Programme
  - Most recently, capture-ready study
- Department of Trade and Industry/industry collaborative projects
  - Project 366 looked at oxyfuel and amine options for Canadian market
  - One current example is Project 407 on advanced supercritical retrofit at coal-fired power plants, including post-combustion with amine and oxyfuel
- British Coal Utilisation Research Association
  - Experimental work on combustion (effect of coal type on ignition)
  - Current projects include Chem Eng PhD on amine solvents and Mech Eng PhD on biomass combustion
- In many of our projects we work actively involve industry
  - ALSTOM, E-On UK, SaskPower and other power utilities, Mitsui Babcock, Air Products…

Tyndall°Centre

UNIVERSITY OF ABERDEEN

BGS 1835

The University of Reading

CAMBRIDGE

UK Carbon Capture and Storage Consortium

PLYMOUTH MARINE LABORATORIES

Part of the Research Councils TSEC Programme

CRANFIELD

THE UNIVERSITY OF EDINBURGH

NOTTINGHAM

UNIVERSITY OF NEWCASTLE

Getting Ready for Carbon Capture and Storage in the UK

UNIVERSITY of GLASGOW

MANCHESTER 1824

UNIVERSITY OF LEEDS

Imperial College London

HERIOT-WATT

UK CSC

Outline of oxyfuel interests

- Developing detailed understanding of coal combustion in O_2/CO_2
  - Original work funded by BCURA, using NIOSH 20 litre ignition chamber
  - Follow-on should start soon, including CFD
- Oxyfuel system design options
  - Initial study under DTI Project 366
- Reliability, Availability Maintainability and Operability (RAMO)
  - Some early work under DTI Project 407 is to be continued in a new project next year

Oxyfuel combustion

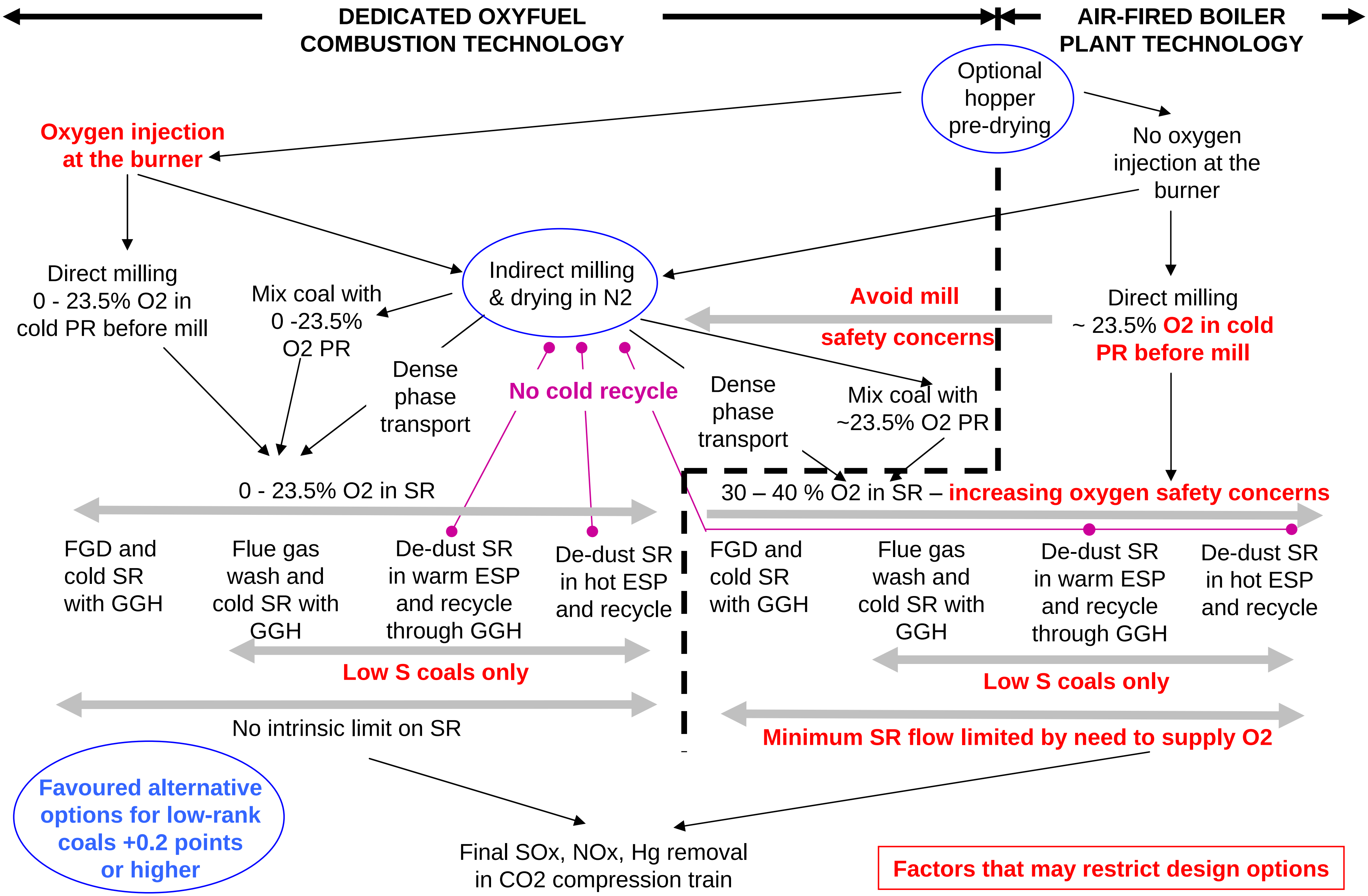
BCURA PROJECT B75
OCT 2004 - OCT 2005
Dr Chi Man

- Different coals behave quite differently
- 21% O2 in CO2 is not always the same as air…
- …30-35% O2 is needed to get the same result

- Follow-on starting soon and will include CFD

NIOSH 20 litre ignition chamber

Alternative Plant Configurations?!



RAMO

- Initial high-level study has identified some points for further consideration/work
  - Air/O_2 switching
  - Part-load performance (ramp rates and efficiency)
  - Use of LOX storage?
- Should be one key activity for our group during 2007?

Summary of some other CO_2 capture research activities in our group

- Desk studies on different CO_2 capture technologies for electrical power generation, mostly coal-fired…
  - Post-combustion capture with amine solvents
  - IGCC
- …including detailed thermodynamic modelling of steam cycles (integration and optimisation)
- CCS economics and strategies for deployment, including capture-ready
- Less well studied applications of CCS
  - Plant flexibility, including synergies with renewables
  - Biomass co-firing to remove CO_2 from atmosphere

Background/motivation for work on post-combustion capture

Six rules for effective post-combustion capture

1. Add heat to the steam cycle at as high a temperature as possible (i.e. be prepared to use best available steam conditions if commercially justified).

2. Reject heat from the steam cycle, in the steam extracted for solvent regeneration, at as low a temperature as possible.

3. Produce as much electricity as possible from any additional fuel used, consistent with rejecting heat at the required temperature for solvent regeneration.

4. Make use of waste heat from CO2 capture and compression in the steam cycle.

5. Use the latest solvent developments.

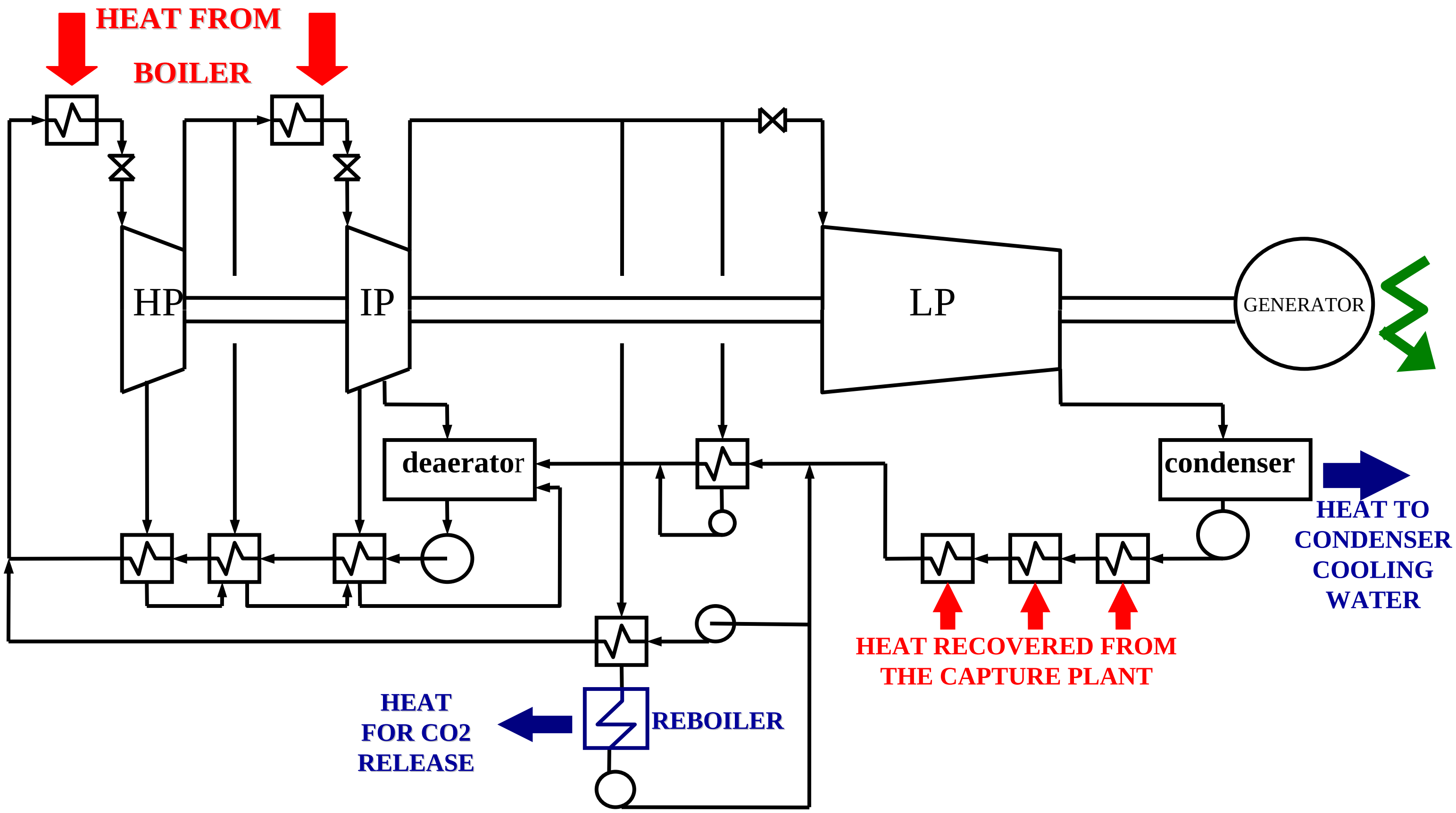
We're now pretty good at this?!

6. Exploit the inherent flexibility of post-combustion capture.

Gibbins et al, *Maximising the Effectiveness of Post Combustion CO_2 Capture Systems*, GHGT7

Thermodynamic Optimisation of Steam Cycles

- Steam cycle modelling for post-combustion capture



Background/motivation for work on post-combustion capture

Six rules for effective post-combustion capture

1. Add heat to the steam cycle at as high a temperature as possible (i.e. be prepared to use best available steam conditions if commercially justified).

2. Reject heat from the steam cycle, in the steam extracted for solvent regeneration, at as low a temperature as possible.

3. Produce as much electricity as possible from any additional fuel used, consistent with rejecting heat at the required temperature for solvent regeneration.

4. Make use of waste heat from CO2 capture and compression in the steam cycle.

5. Use the latest solvent developments.

6. Exploit the inherent flexibility of post-combustion capture.

A lot of our ongoing work focuses on these…

Gibbins et al, *Maximising the Effectiveness of Post Combustion CO_2 Capture Systems*, GHGT7

Interpretations of solvent developments and plant flexibility (for post-com.)

- Amine solvent developments, integrating with steam cycle
- Capture-ready principles
  - Definitions and requirements
  - Design implications
- Potential to retrofit CO2 capture to existing plants?
- Options for improved operability and flexibility
  - Including potential for amine storage
- Synergies with renewables
  - Biomass co-combustion
  - Balancing renewable intermittency

- Lots of experience to apply to oxyfuel plants too?!

Summary

- CCS research at Imperial College London
- Some key projects and collaborations
- Summary of oxyfuel research activities
  - Combustion: experimental work on ignition (CFD soon)
  - System configuration options
  - Integration opportunities
  - Reliability, availability, maintainability and operability (RAMO)
- Brief overview of some other CO_2 capture activities

Imperial College London

Overview of Oxyfuel (and some other CO_2 Capture) Research Activities

within the Energy Technology for Sustainable Development Group, Department of Mechanical Engineering, Imperial College London

Hannah Chalmers, Mathieu Lucquiaud,
Jon Gibbins (and a few others)

hannah.chalmers@imperial.ac.uk
m.lucquiaud@imperial.ac.uk

Appendix

Extra Details on Post-Combustion Capture Activities

Interpretations of solvent developments and plant flexibility - 1

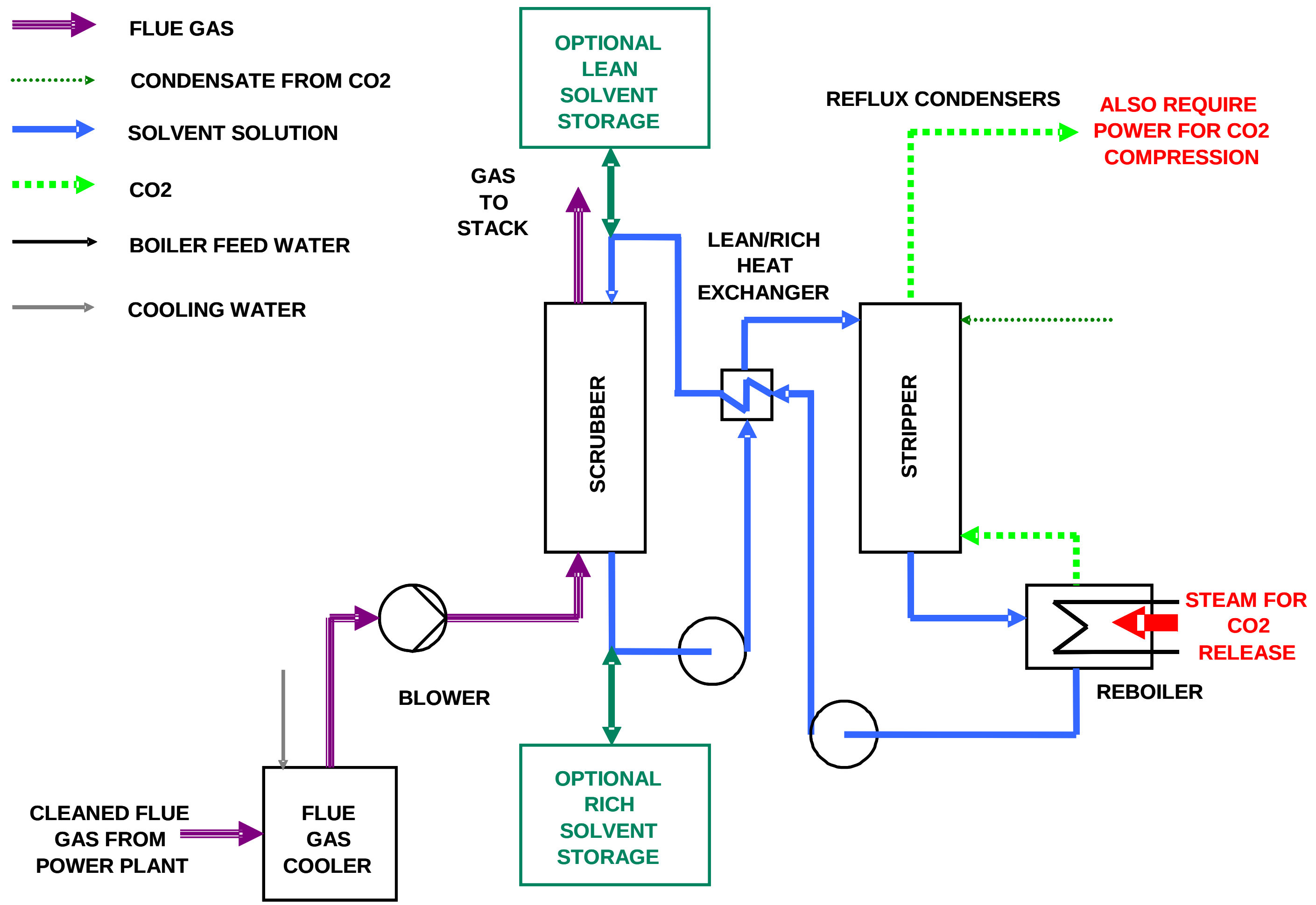
- Amine solvent developments
- Joint work with Imperial College Chemical Engineering Department
- Two ongoing, but related, projects
- Both are improving our understanding of solvents and tackling issues that are not well covered in previous studies
  - Need to fully integrate amine solvent regeneration process with steam cycle, including heat recovery
  - Part load performance

Interpretation of solvent developments and plant flexibility - 2

- Capture-ready power plant (and retrofit issues)
- Joint work with various industrial players (including E.On UK, Mitsui Babcock, ALSTOM)
- Definitions and requirements
  - Technical and economic
  - Some easy: space on site and design study
  - Some more difficult: location and plant type
  - Pre-investments decisions based on overall plant capital and operation lifetime costs
- Design implications

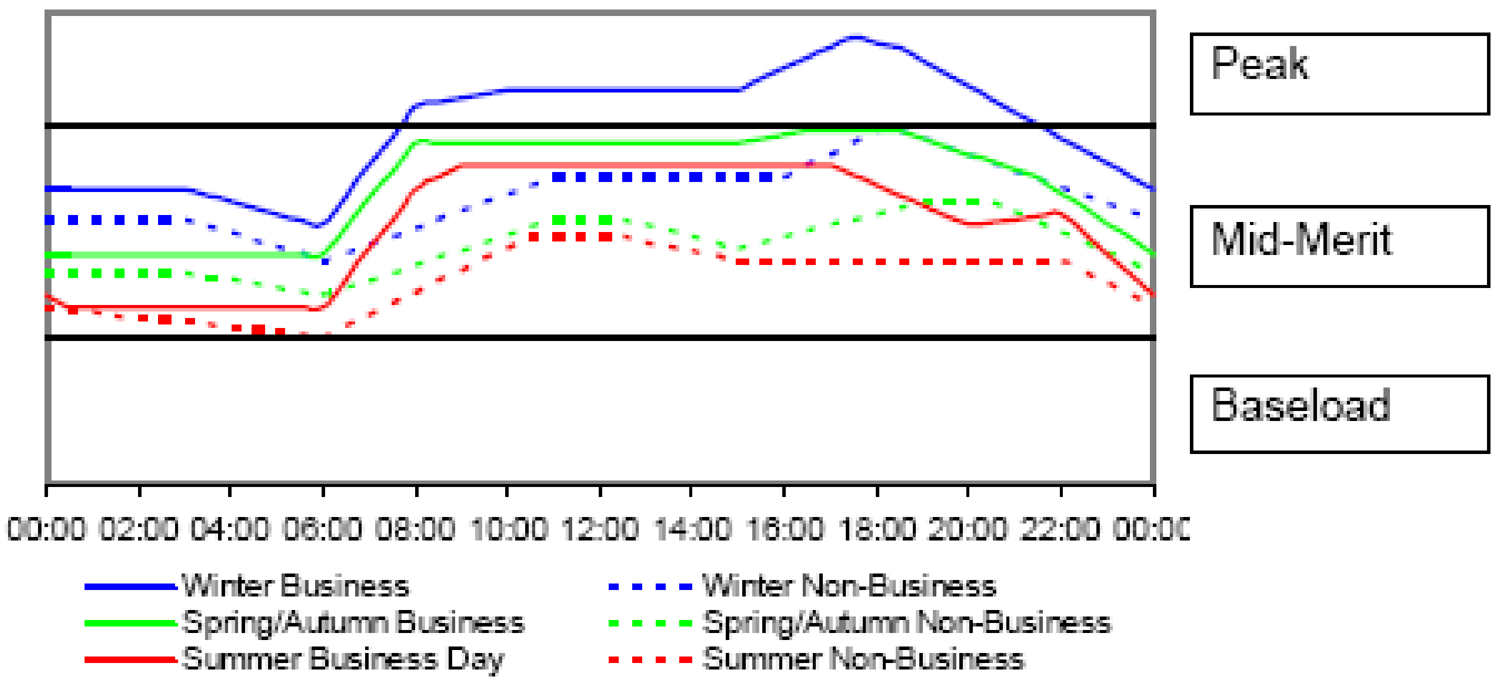
Interpretation of solvent developments and plant flexibility - 3

- Review of plant operability and flexibility options/issues – including potential for amine storage…



Interpretation of solvent developments and plant flexibility - 4

- Synergies with biomass and other technologies in an electricity grid…



Demand curves based on SCAR report, published in support of 2003 UK Energy White Paper, Peak assumed to be >80% of peak load
From Chalmers and Gibbins (2006),
29th IAEE International Conference, Potsdam, Germany

Thermodynamic Optimisation of Steam Cycles

- Steam cycle modelling for post-combustion capture
  - Thermodynamic integration between power plant and capture plant
  - Reduce the energy penalty
  - Optimisation model between steam power plant and amine capture plant is progressing…
  - …but still some work to do on fully understanding amine capture process and potential improvements

Research Activities on Oxyfuel Combustion at IVD, Universität Stuttgart

Dipl.-Ing. P. Mönckert, M.Sc. B. Dhungel, Dipl.-Ing. D. Reber,
Dipl.-Ing. J. Maier, Prof. Dr. techn. G. Scheffknecht

Developments in Oxy-Combustion Technology for Power Plants with CCS – A Young Researchers Forum
Hamburg University of Technology, 8th December 2006

Contents

Universität Stuttgart

1. IVD's Structure and Work Areas
2. Test Facilities
3. Oxyfuel Combustion at IVD
4. Results
5. Outlook

Structure and Work Areas of IVD

Universität Stuttgart

Prof. Dr.-Ing. Helmut Seifert
Forschungszentrum Karlsruhe GmbH

Institute of Techn. Chemistry
Thermal Treatment of Waste

- **Prof. Dr.-techn. G. Scheffknecht** – Director
  - **Departments**
    - **Dipl.-Ing. J. Maier** – Combustion Systems and Steam Boilers
    - **Prof. Dr.-Ing. G. Baumbach** – Air Pollution Prevention
    - **Dipl.-Ing. H. Thorwarth** – Fuels and Measurement Techniques
    - **Dr.-Ing. R. Berger** – Decentralized Energy Conversion
    - **Prof. Dr.-Ing. PD U. Schnell** – Combustion and Steam Boiler Simulation
    - **Dipl.-Ing. T. Weißbach** – Power Generation and Automatic Control

Test Facilities at IVD

Universität Stuttgart

Lab Scale

- **Atmospheric drop tube furnace**
- Atmospheric drop tube furnace
- Slagging and fouling experimental rig
- Flameless combustion burner test rig

Pilot Scale

- **0.5MW$_{th}$ Pulverised fuel combustion rig**
- Atmospheric fluidised bed test rig (bubbling/circulating)
- Pressurised fluidised bed test rig (bubbling)
- **Pressurised entrained flow reactor**

Investigation parameters:
pyrolysis
gasification
homogeneous/ heterogeneous reaction
flameless combustion
ash formation and behavior
slagging, fouling
fuel conversion under pressurized conditions
flue-gas cleaning
…

Fuel preparation:

- Hammer and impact mills → preparation of bituminous coal
- Beater mill → preparation of lignite/ brown coal
- Several other mills for preparation of biogenic fuels,
  co-combustion material (SRF), etc.

Test Facilities - 20kW$_{th}$ coal combustion reactor

Atmospheric drop tube furnace

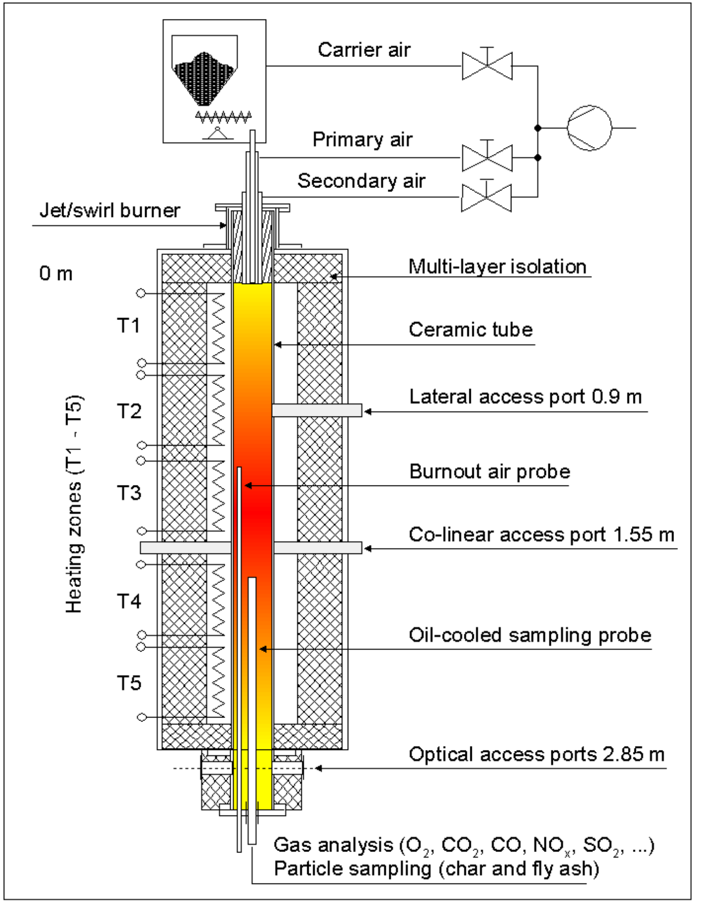
Universität Stuttgart

General caracteristics:

- Furnace: Ceramic tube
- Length of furnace: 2,500 mm
- Diameter: 200 mm
- 5 electrically heated zones (up to 1400°C)
- **Oxyfuel** concentrations of carrier, primary and secondary gas streams separately adjustable
- Co-linear optical access at 1,550 mm

Measurement parameters (fuel characterisation):

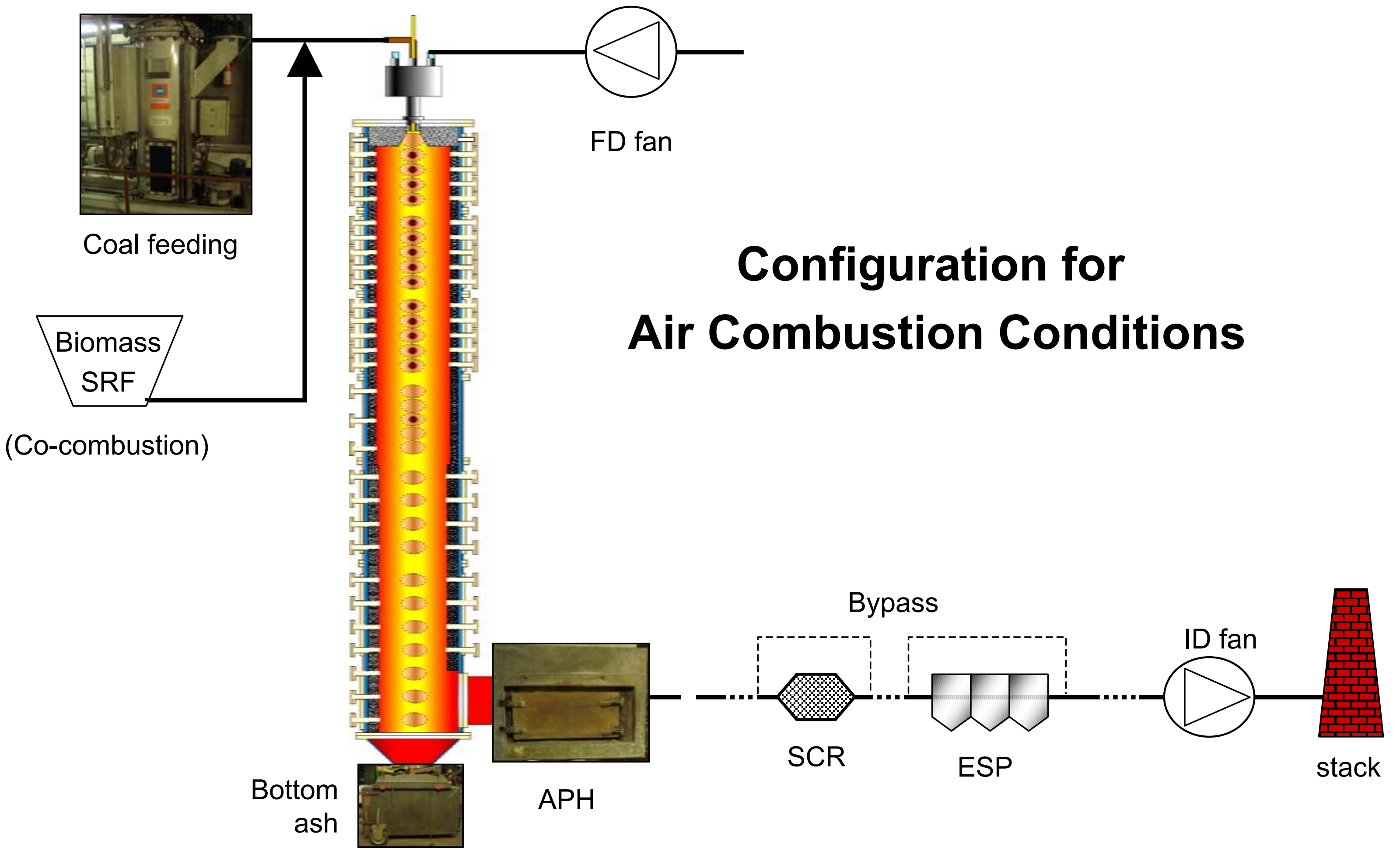
- Gas emission profiles (oil-cooled probe)
- Gas temperature profiles (suction pyrometer)
- Particle temperatures (2-color-pyrometry)
- Particle sampling (profile and fly-ash)
- Deposit sampling



Test Facilities - 0.5MW$_{th}$ Unit

Pulverised fuel combustion facility

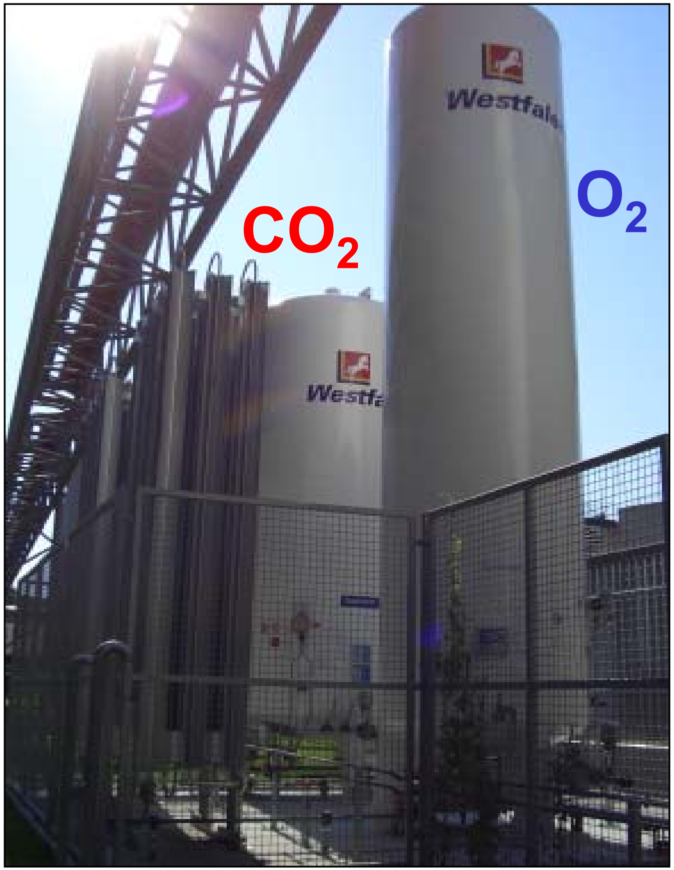
Universität Stuttgart



Configuration for
Air Combustion Conditions

Modifications for Oxyfuel Combustion

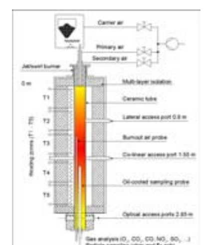
Universität Stuttgart



storage tanks

gas distribution

others



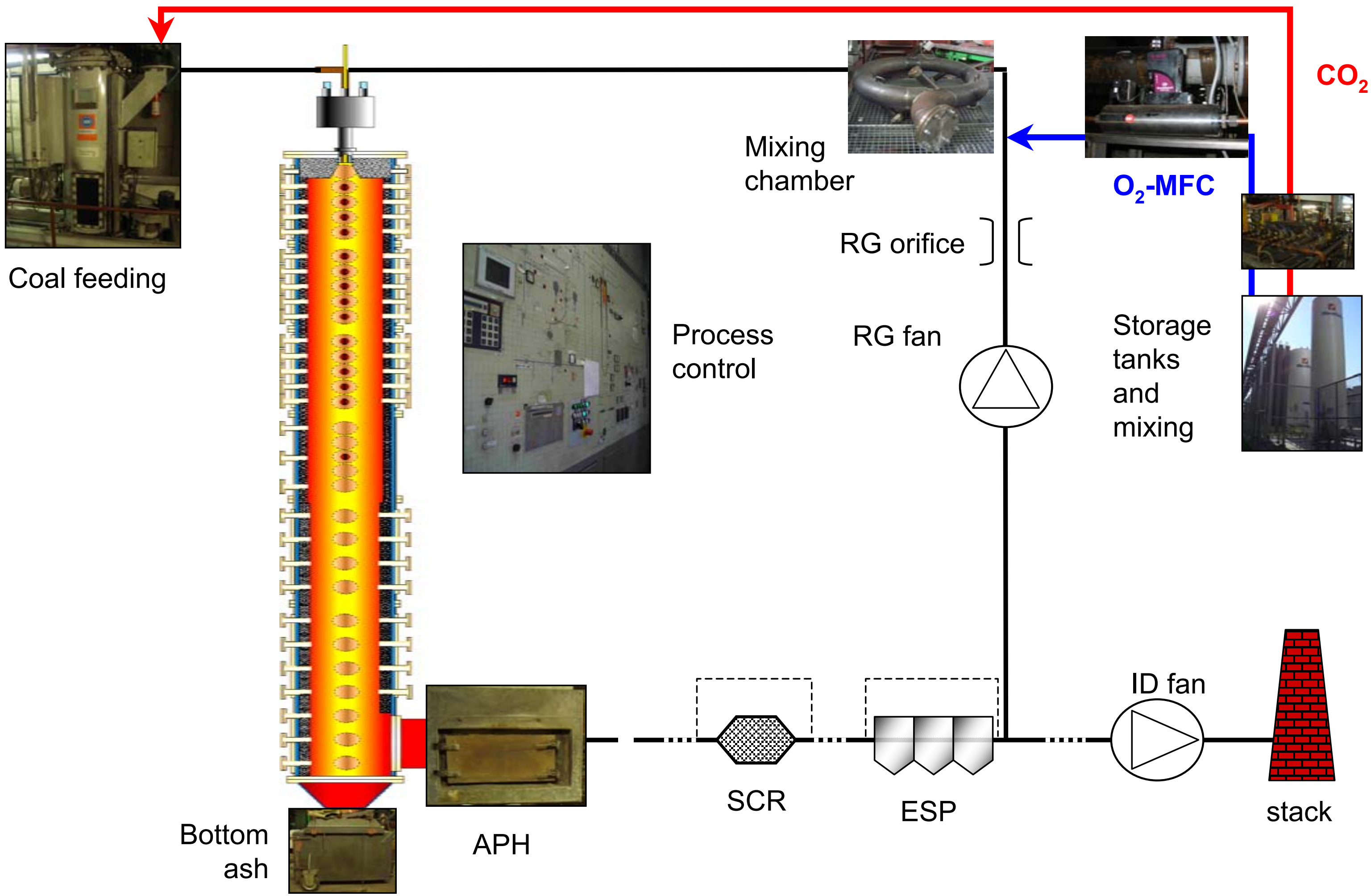
$20kW_{th}$

$0.5MW_{th}$

consumers

$0.5MW_{th}$ Unit
Modifications for Oxyfuel Combustion Conditions

Universität Stuttgart



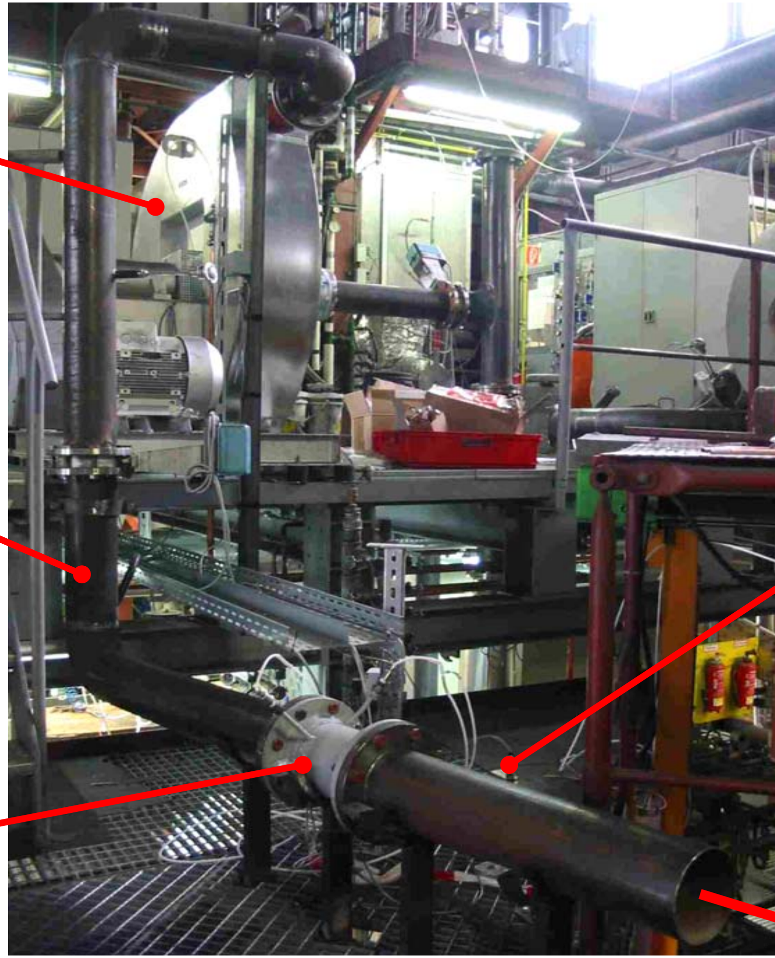
$0.5MW_{th}$ Unit
Modifications for Oxyfuel Combustion Conditions

Universität Stuttgart

re-circulation ventilator

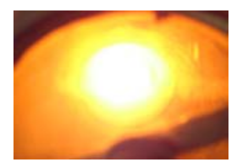
duct for re-cycled flue-gas

Venturi orifice



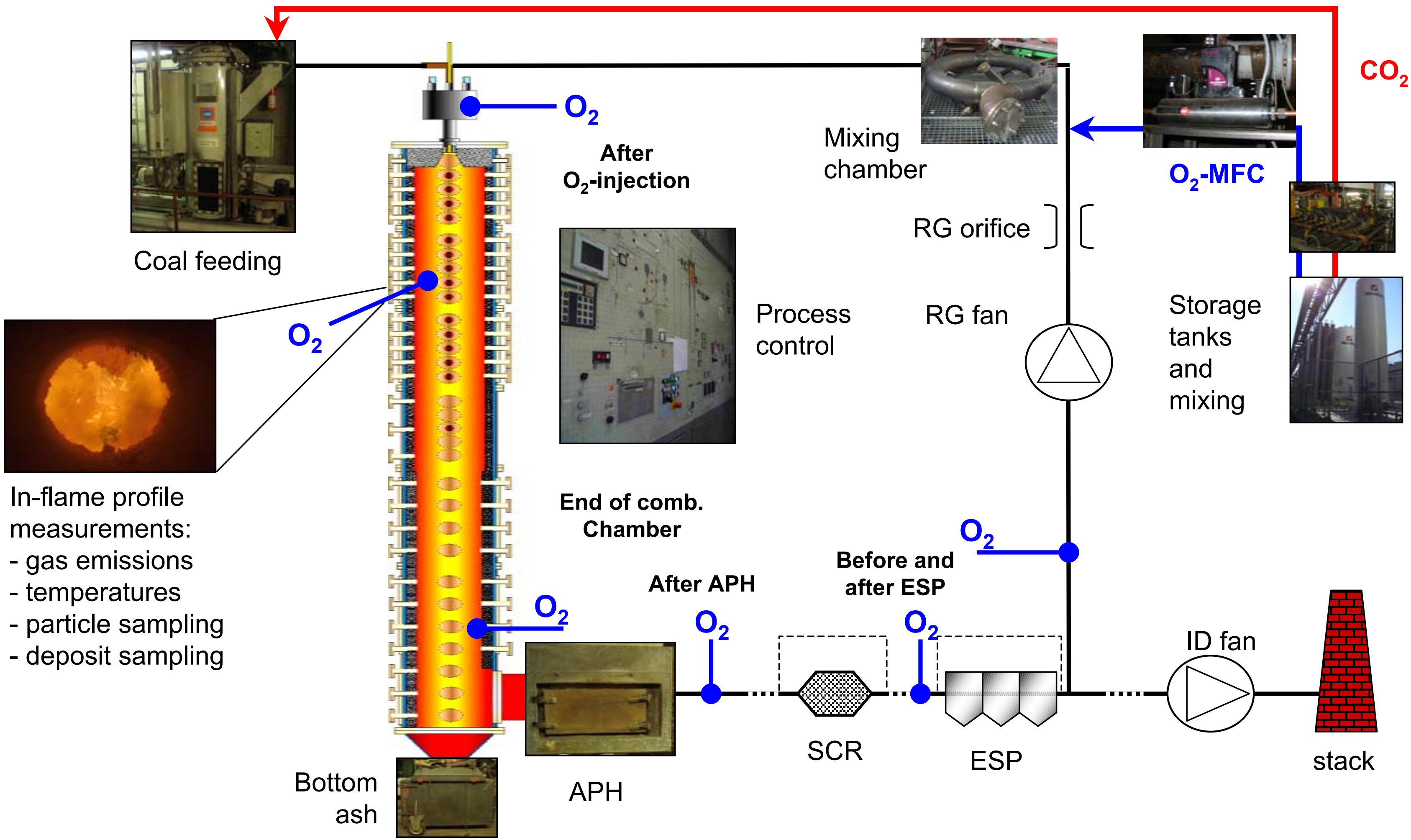
O_2 injection system (MFC, injector)

to furnace



0.5MW$_{th}$ Unit
Modifications for Oxyfuel Combustion Conditions

Universität Stuttgart



Oxyfuel Research Topics

Universität Stuttgart

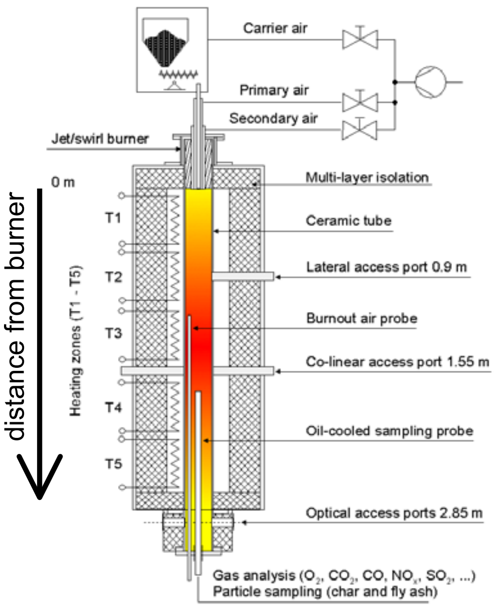
Investigation of

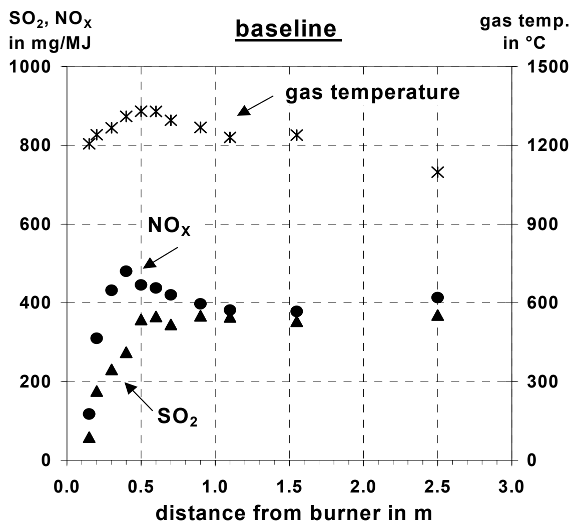
- **Fuel characteristics (lab unit)**
  - particle ignition temperature
  - gas emission behaviour under staged and un-staged conditions, impact of flue-gas re-circulation
  - ash quality
- **Flame stability and basic oxyfuel burner set-up (lab and pilot unit)**
  - variation of burner set-up
  - variation of oxygen injection
- **Burnout and emission behaviour (lab and pilot unit)**
  - gas emission profiles
  - gas temperature profiles
  - radiation intensity profiles (Chalmers UT)
  - fly-ash profiles
- **Slagging, fouling and fly ash behaviour (lab and pilot unit)**
  - fly-ash and burnout characterisation
  - exposure of deposition probes (Vattenfall UAB)
- **Operational procedures (0.5MW_{th} pilot unit)**
  - start-up/ shut-down procedures
  - identification of air-inleakage
  - switch from air to oxyfuel operation
  - parameter optimisation (variation of O_2-injection, recycle rate, …)
  - maximisation of CO_2 concentration
  - reference flame definition

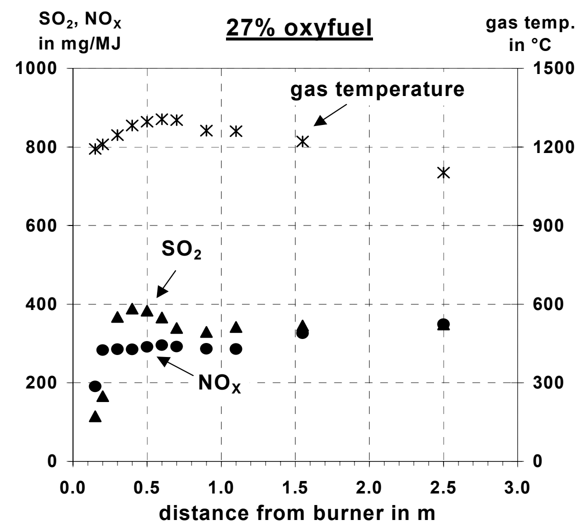
Results
Fuel Characterization under Oxyfuel Conditions

Universität Stuttgart

Gas emissions and gas temperature profiles: air vs. 27% oxyfuel (Kleinkopje bituminous coal)







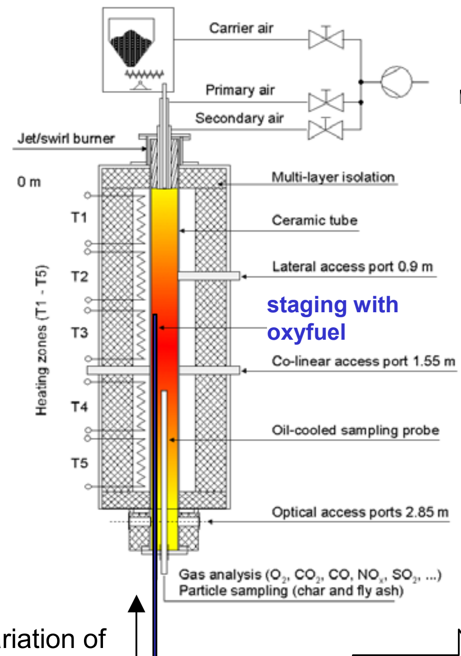
Un-staged combustion:

NO_X emission for referred to energy input equal or inferior at oxyfuel conditions compared to air conditions, SO_2 is not influenced.

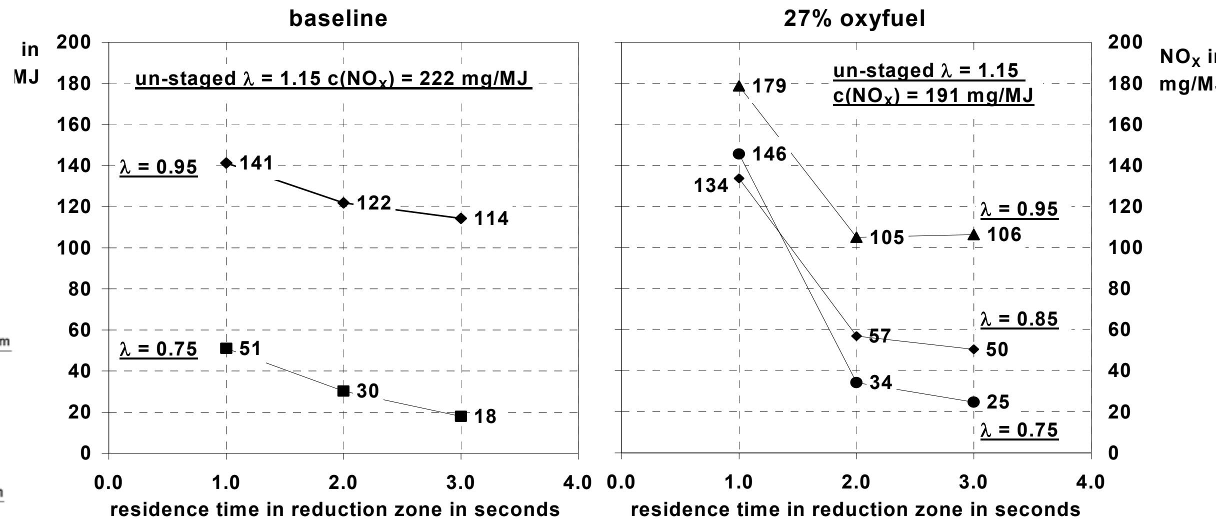
Results
Fuel Characterization under Oxyfuel Conditions

Universität Stuttgart

Effect of oxyfuel staging on NO_X emission rate (Lausitz lignite)



variation of residence time



Staged combustion:

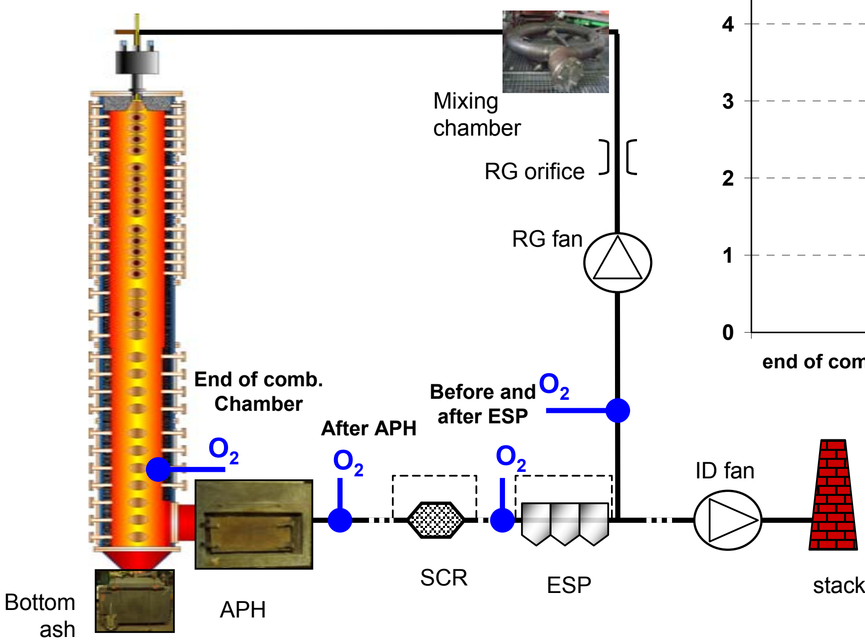
NO_X emission rate decreases significantly for decreasing stoichiometric ratio and with increasing residence time in the reducing zone

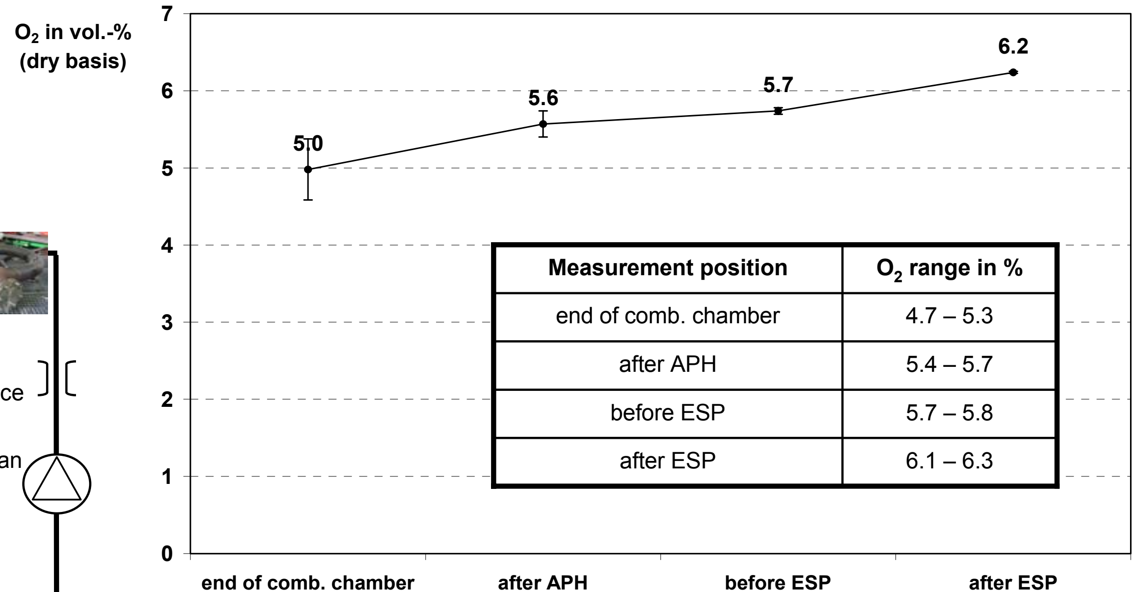
NO_X is given referred to NO_2

Optimization of 0.5MW$_{th}$ Unit
Identification of air-inleakages

Universität Stuttgart

O_2 profile under oxyfuel and re-circulation conditions

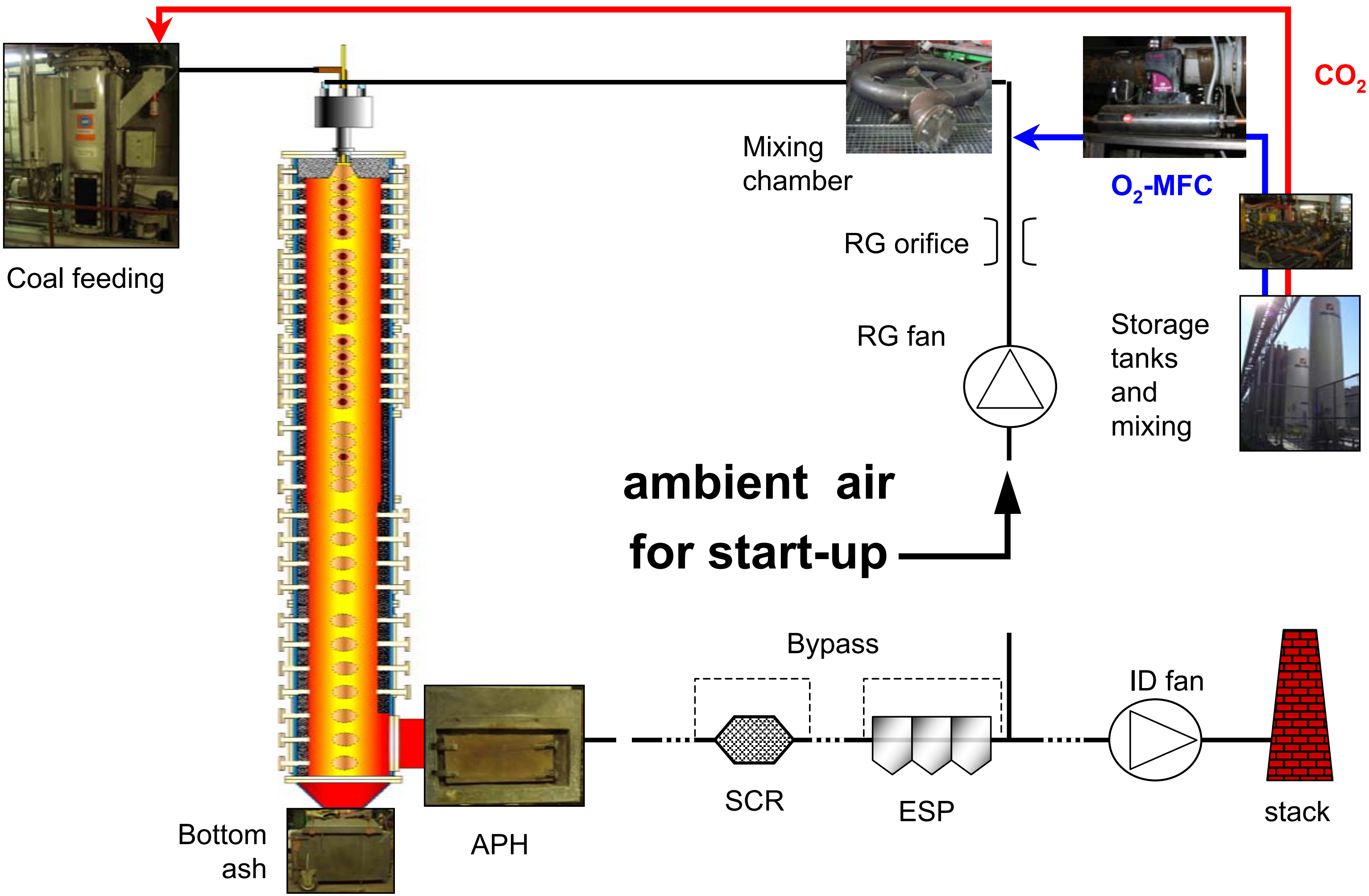




Measurement position	O_2 range in %
end of comb. chamber	4.7 – 5.3
after APH	5.4 – 5.7
before ESP	5.7 – 5.8
after ESP	6.1 – 6.3

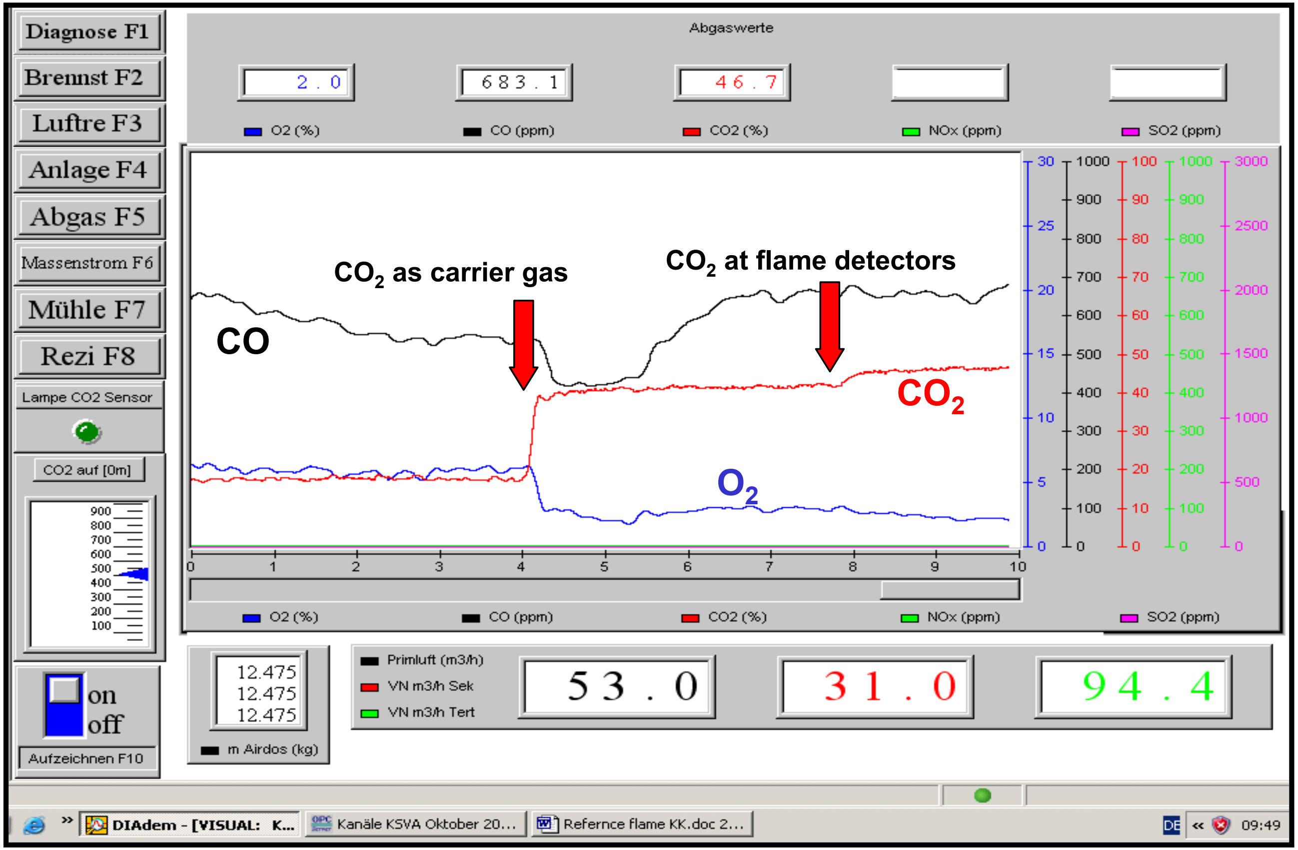
$0.5MW_{th}$ Unit
Modifications for Oxyfuel Combustion Conditions

Universität Stuttgart



Operational behaviour:
Switch from once-through to re-circulation mode

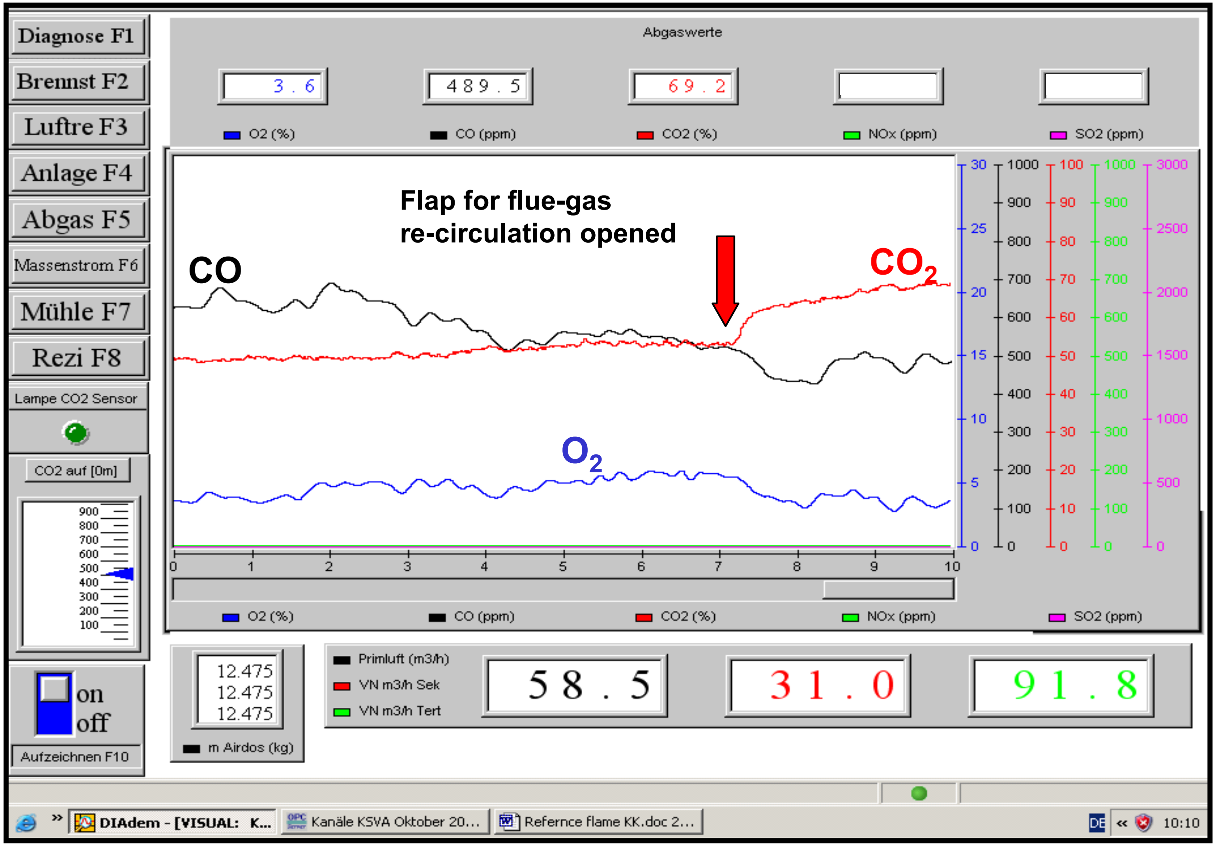
Universität Stuttgart



09:49 h: CO_2 instead of air as carrier gas, CO_2 as cooling for flame detector

Operational behaviour:
Re-circulation of flue-gas and reduction of ambient air supply (I)

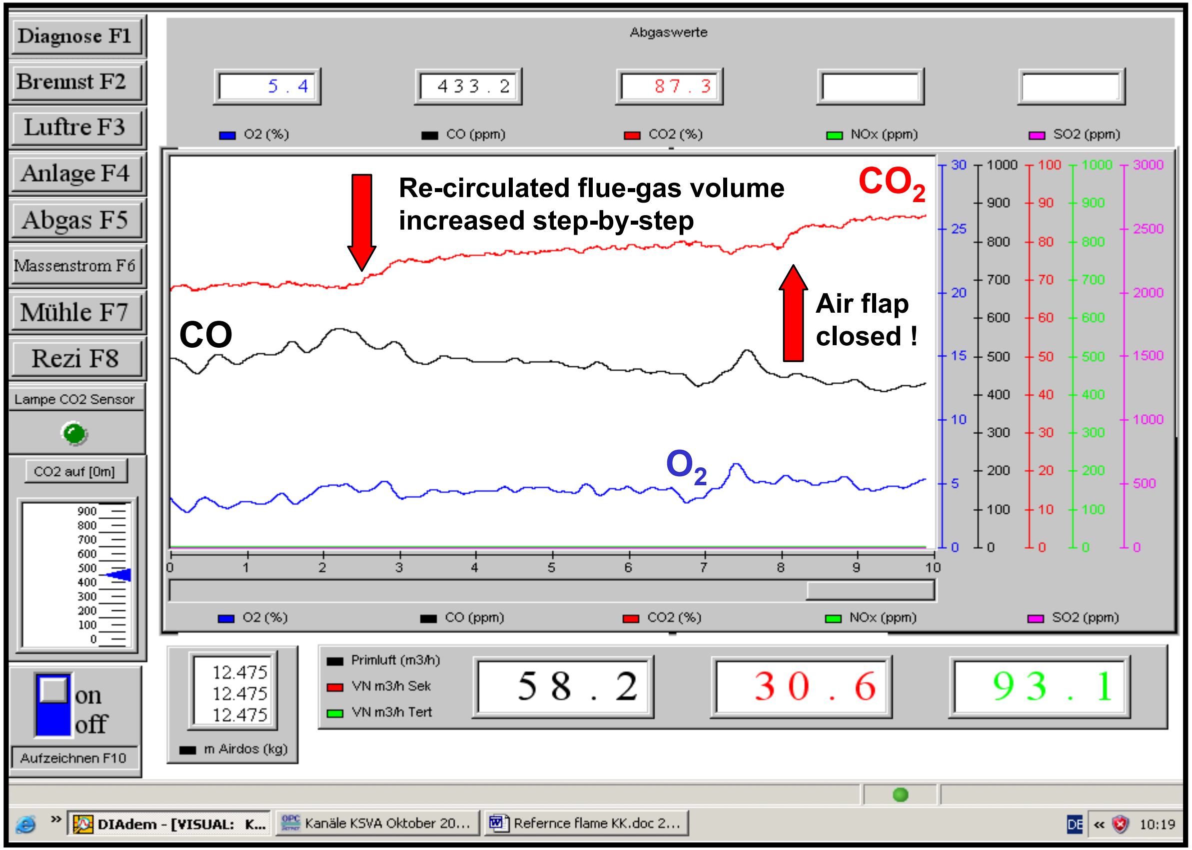
Universität Stuttgart



10:10 h: flue-gas re-circulation started

Operational behaviour:
Re-circulation of flue-gas and reduction of ambient air supply (II)

Universität Stuttgart

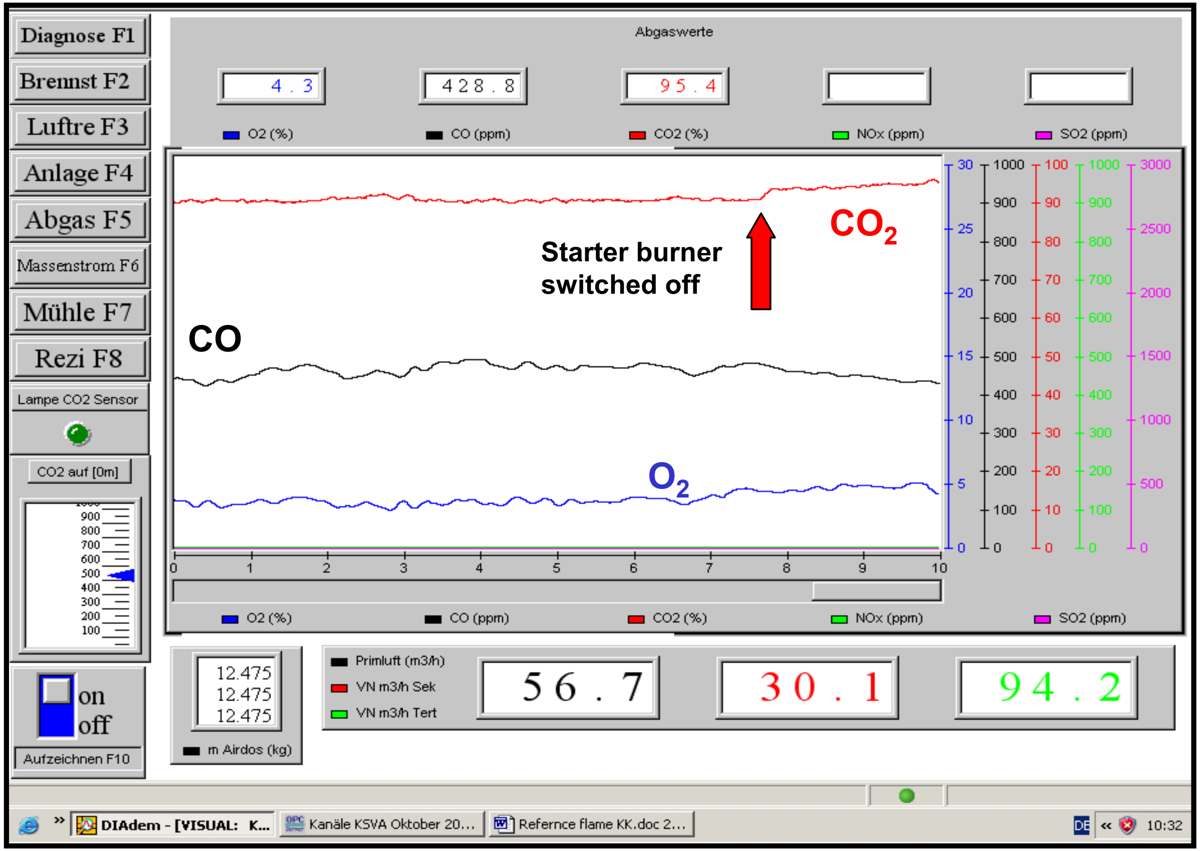


10:19 h: ambient air flap closed tightly; remaining air entry through starter burner

Operational behaviour:

Re-circulation of flue-gas and reduction of ambient air supply (III)

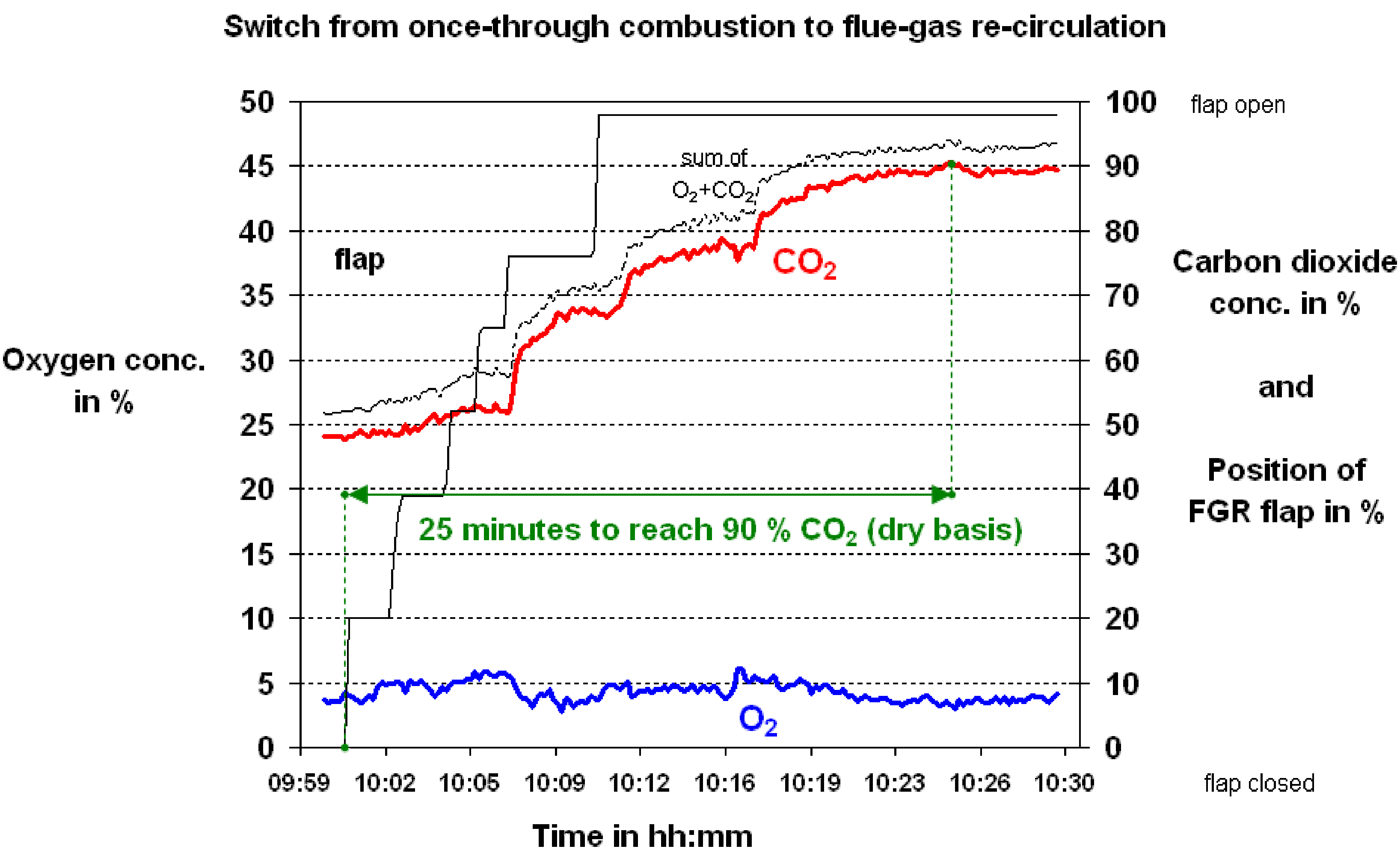
Universität Stuttgart



10:32 h: starter burner switched off, maximisation of CO_2 concentration

Results
Oxyfuel Combustion at 0.5MW$_{th}$ Unit

Universität Stüttgart



Results
Oxyfuel Combustion at 0.5MW_{th} Unit

Universität Stuttgart

- Air in-leakage minimised

- Transmission from once-through to oxyfuel combustion with flue-gas re-circulation successful

- Flame ignition stable despite fuel dosing with pure CO_2

- Stable operation over several hours

- Quick accumulation of CO_2 in flue-gas

Outlook and Work in the Next Months

Universität Stuttgart

Operational

- Implementation of new pre-heater for adjusting temperature of recycled flue-gas
- Recycle rate variation
- Definition of reference flames for various fuels at air and oxyfuel conditions
- Burner optimisation (oxygen injection)

Combustion Characteristics

- Gas temperature and global temperature profiles (→ heat flux, input for simulation)
- Gas emission behaviour under recycle conditions: NO_X behaviour, SO_2 and CO
- Radiation intensity (CHALMERS)
- Deposition sampling, material testing and corrosion probes exposure (with VUAB)
- Investigation of ash quality under recycle conditions fly-ash

Institute of Energy Systems

Prof. Dr.-Ing. Alfons Kather

Christian Hermsdorf
Mathias Klostermann
Karl Mieske

Institute of Thermal and Separation Processes

Prof. Dr.-Ing. Rudolf Eggers

Daniel Köpke

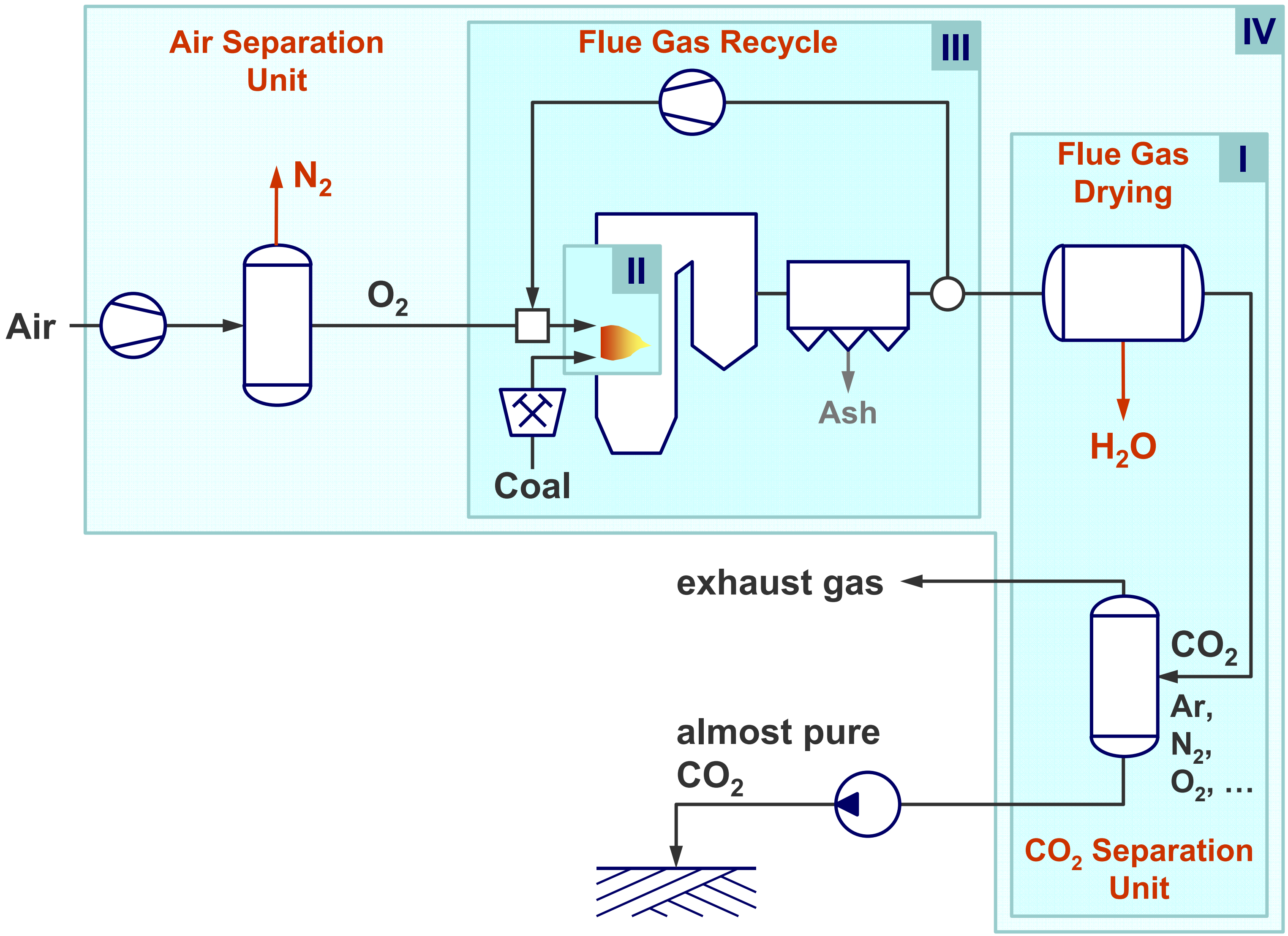
Technische Universität Hamburg-Harburg

Oxyfuel Process for Hard Coal with CO2-Capture

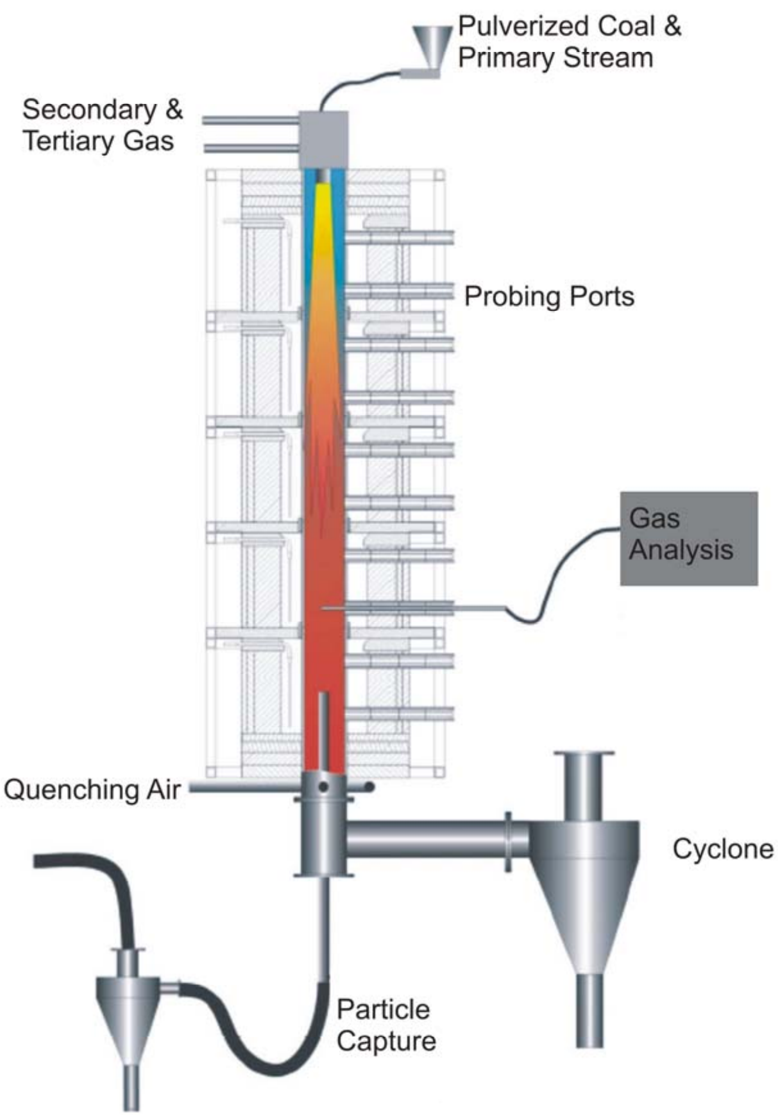
Current Research at TUHH

Young Researchers Meeting,
December 8th, 2006, Hamburg

TUHH Technische Universität Hamburg-Harburg



Entrained Flow Reactor



Combustion capacity: 20 kW

Heated ceramic tube:

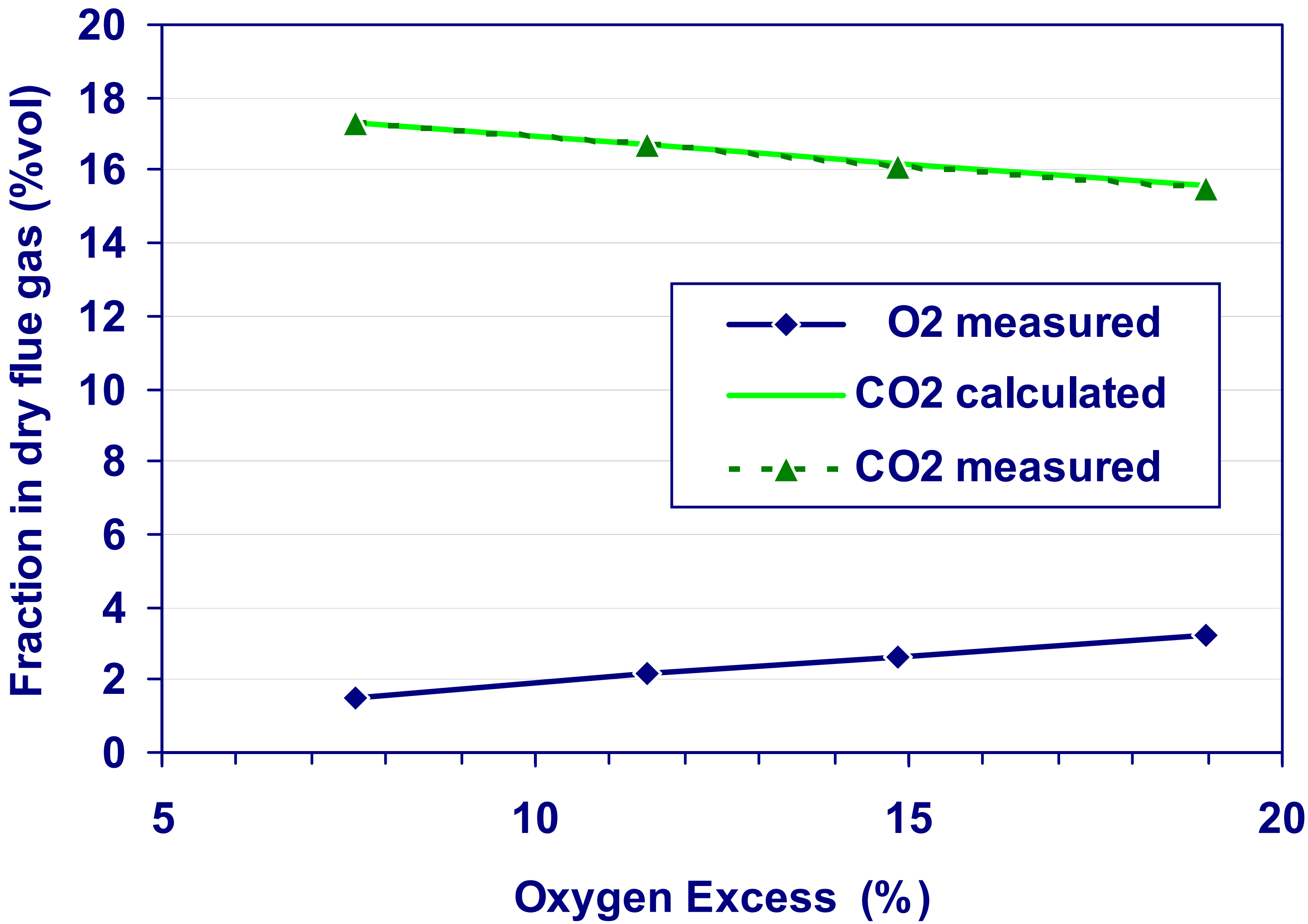
∅150 mm, 2 m length,
5 independent segments,
900 – 1600 °C

Artificial combustion atmospheres by mixing O_2, CO_2, N_2, NO, SO_2, steam, and air

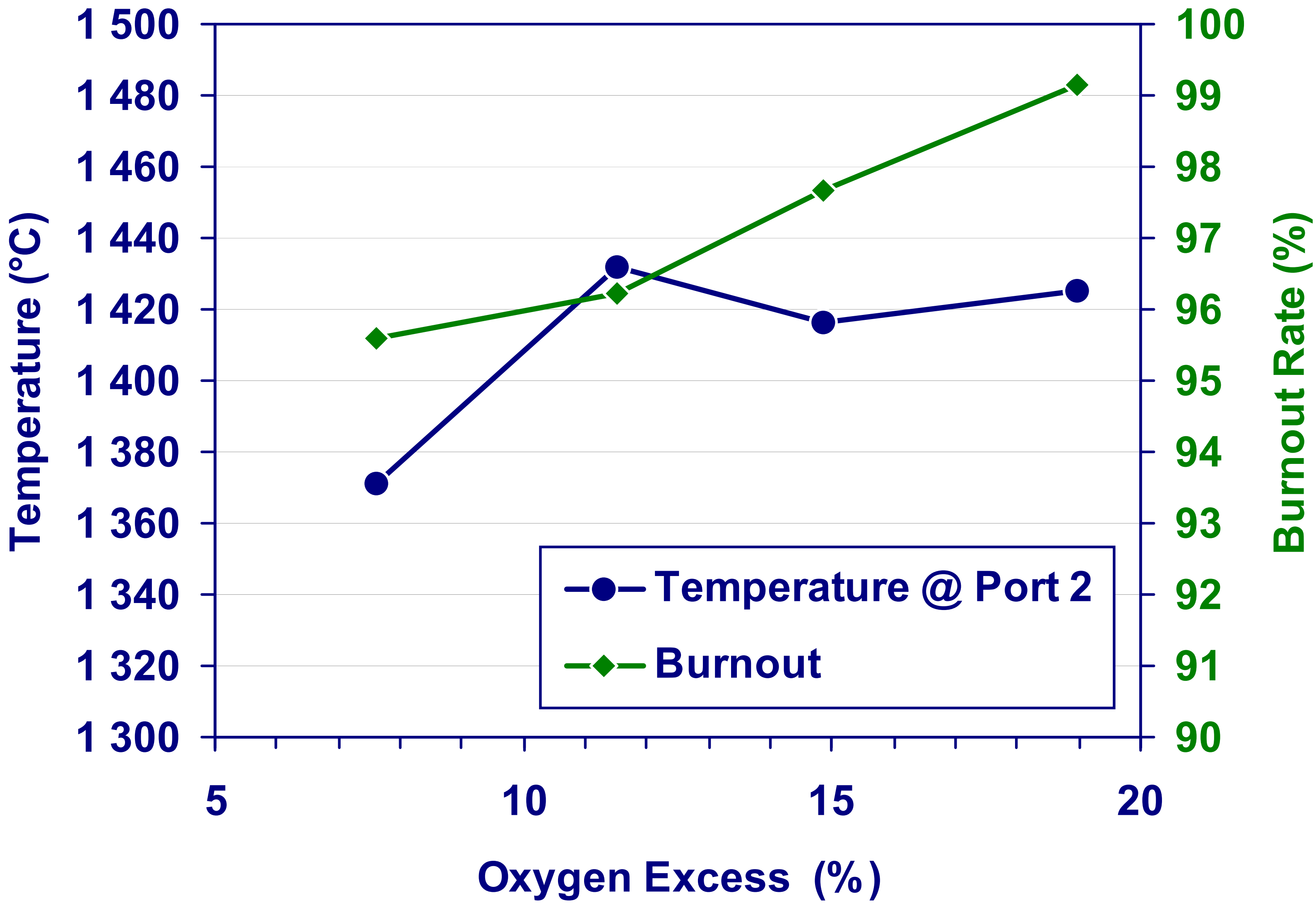
➡ constant combustion conditions

Primary, secondary, tertiary stream and possibility of feed gas staging

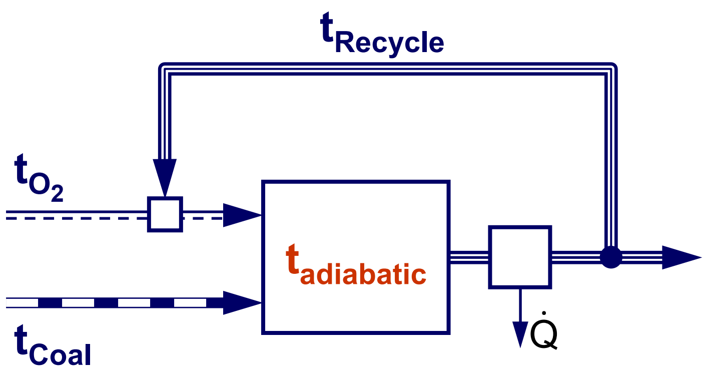
Measurement of NO, NO_2, CO, CO_2, O_2, SO_2, and gas temperature



Fraction in dry flue gas (%vol)
0
2
4
6
8
10
12
14
16
18
20
5
10
15
20
Oxygen Excess (%)
O2 measured
CO2 calculated
CO2 measured


1 500
1 480
1 460
1 440
1 420
1 400
1 380
1 360
1 340
1 320
1 300
Temperature (°C)
100
99
98
97
96
95
94
93
92
91
90
Burnout Rate (%)
5
10
15
20
Oxygen Excess (%)
Temperature @ Port 2
Burnout

Factors influencing the Recycle Requirement



- **Condition:**

  $t_{adiabatic\ w/\ Air} = t_{adiabatic\ w/\ O_2+Recycle}$

- **Underlying assumptions:**

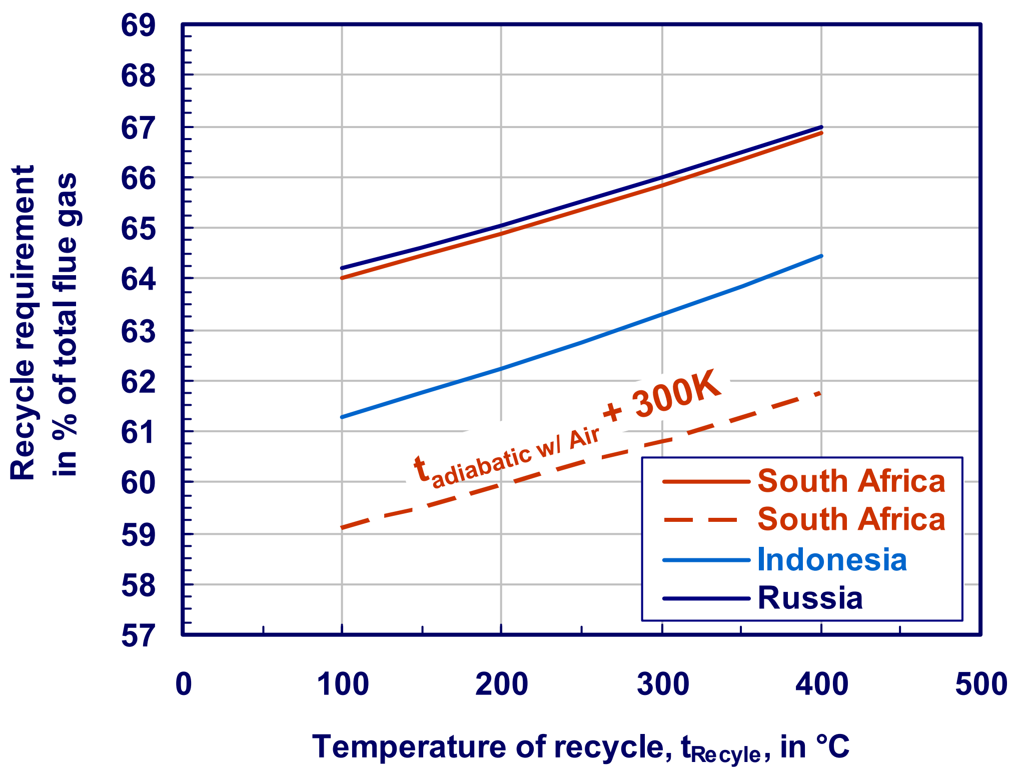
  t_{Air} = 320 °C

  t_{O_2} = 20 °C

  t_{Coal} = 40 °C

  O_2-excess: 15 %

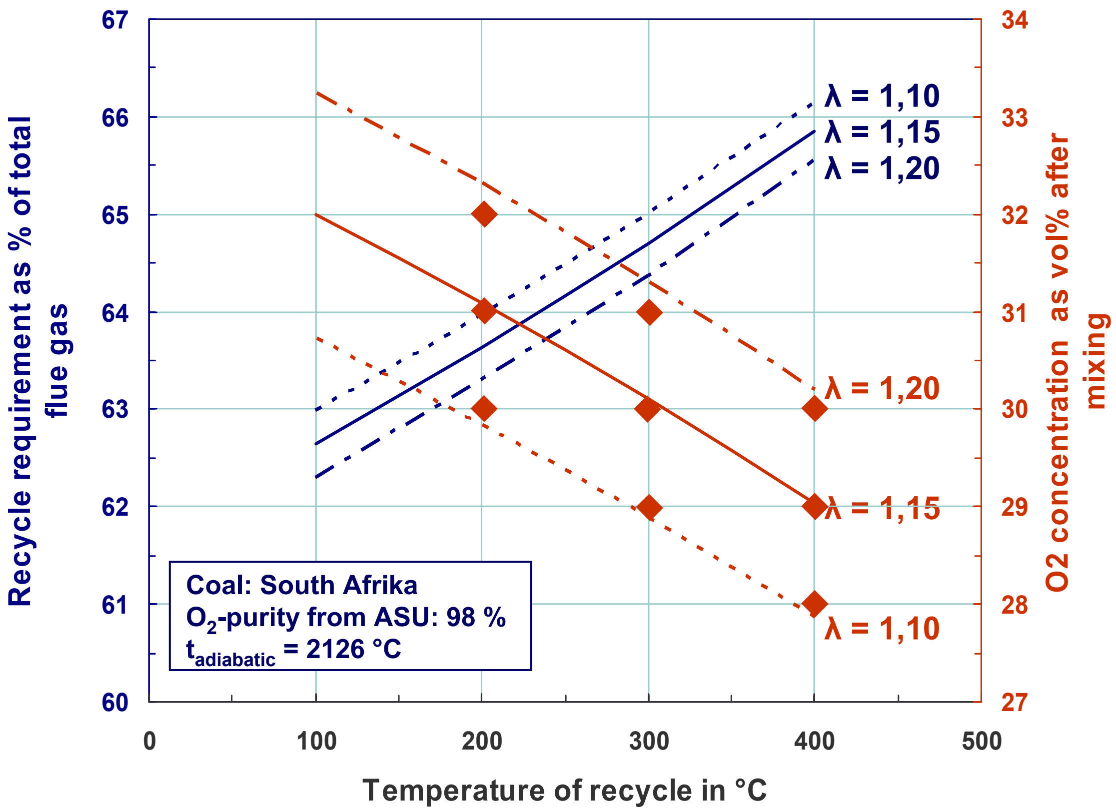
  O_2-purity: 98 %



	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

Oxygen Concentration in the Combustion Atmosphere

- **First approach:** Oxygen and recycled flue gas are mixed completely before combustion
- **Feed-gas composition:** is calculated assuming complete combustion



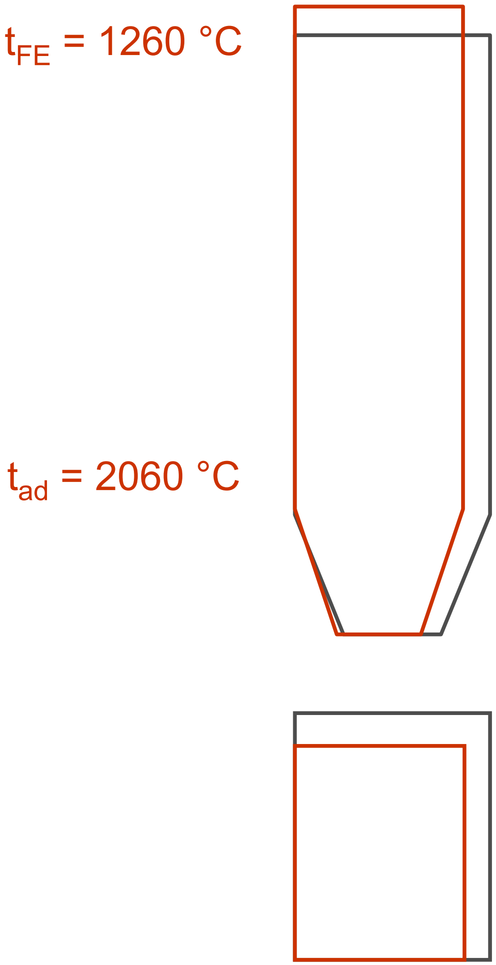
To reach an equal adiabatic temperature the oxygen concentration

- rises by reducing the recycle,
- is always above 21 vol%.

- **First combustion experiments (◆)**

Boiler Design Considerations

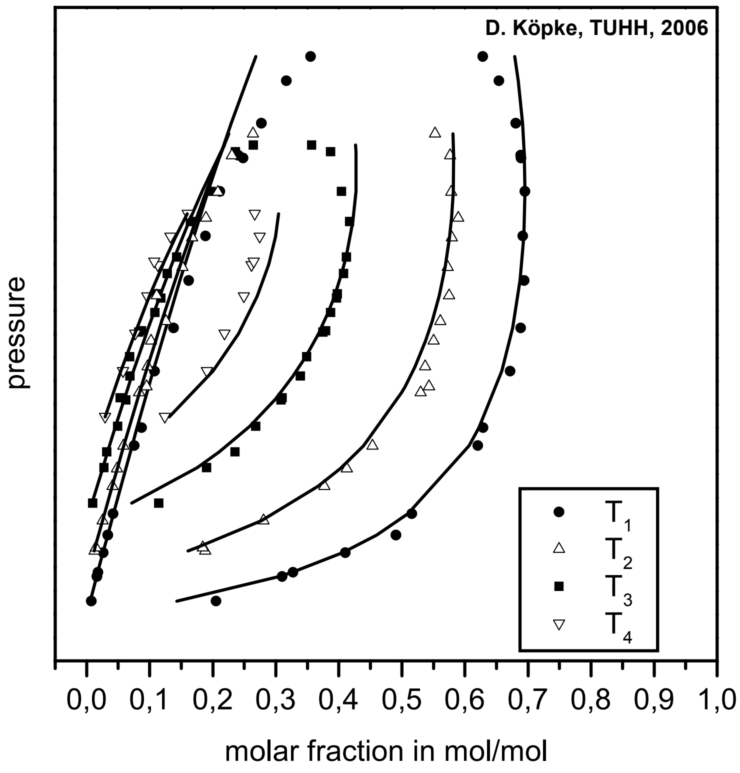
Comparison of the furnace dimensions of a conventional boiler with an Oxyfuel boiler of equal thermal power

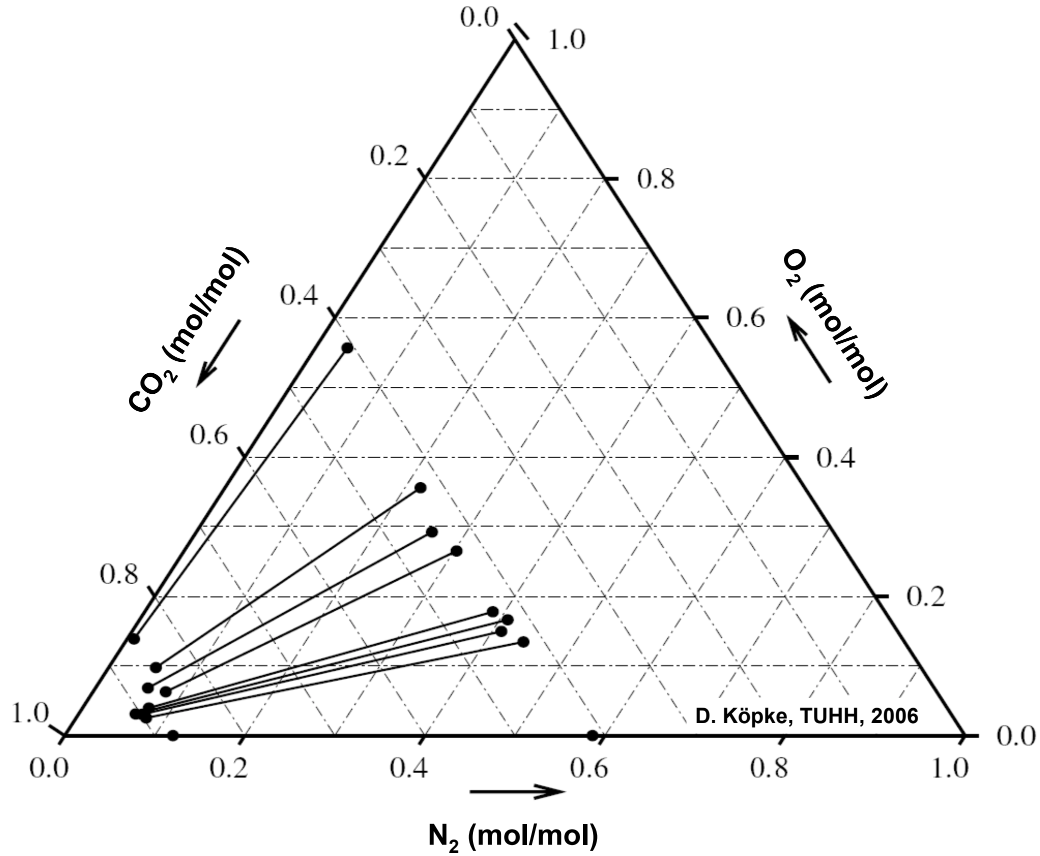


- ≈ 15 % lower flue gas mass stream
- ≈ 22 % higher density of the flue gas
  - ➡ ≈ 30 % smaller cross section of furnace
  - ➡ ≈ 17 % smaller circumference of furnace
  - ➡ furnace ≈ 17 % higher with unchanged heat transfer

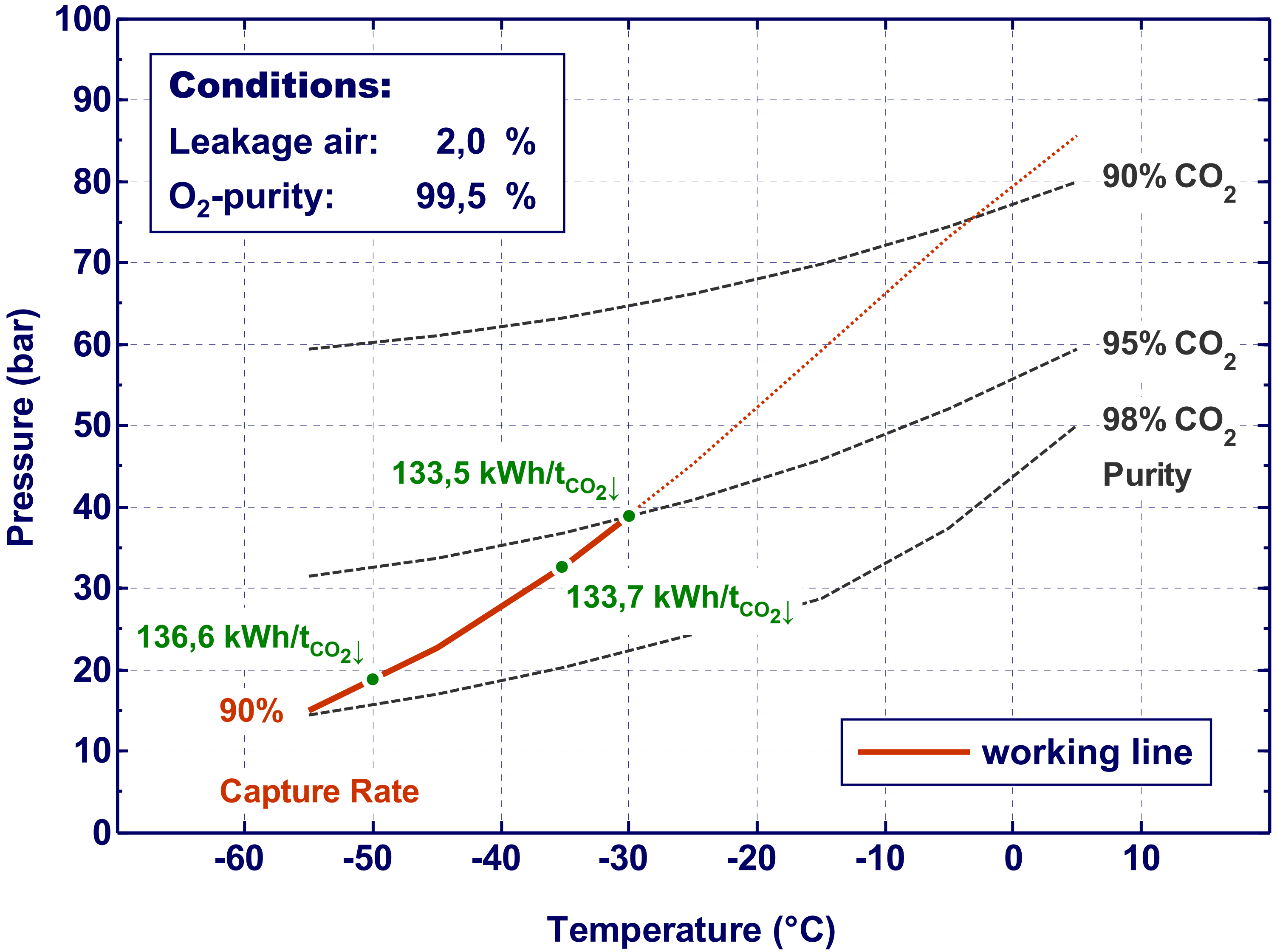
- Improved radiant heat transfer (H_2O, CO_2, dust) leads to ≈ 5 % higher furnace

- Binary phase equilibria measurements
- Multi component phase equilibria measurement



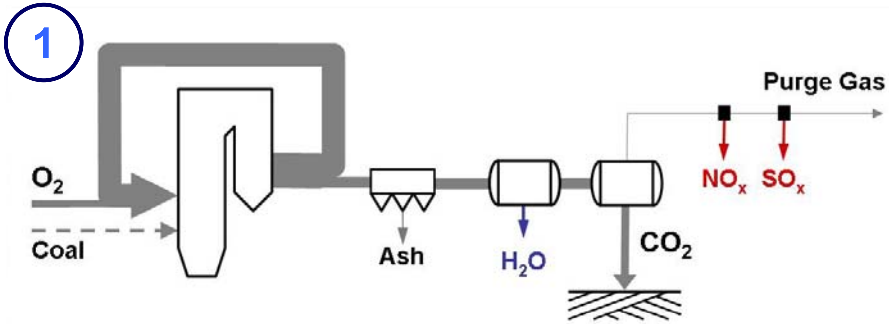


p-T-diagram for single-stage cryogenic CO_2-liquefaction

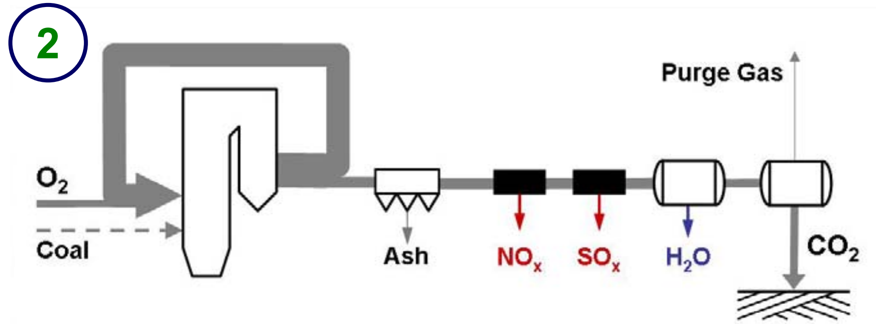


Flue Gas Treatment and CO_2-Purity

1

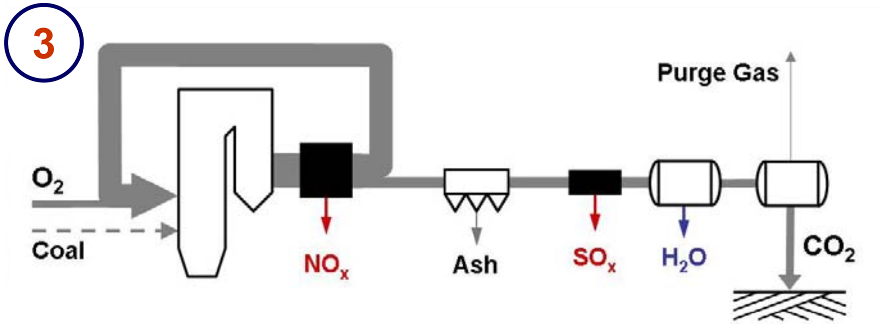


2



Basic Conditions:
Leakage air: 1.0 %
O_2-purity: 99.5 %

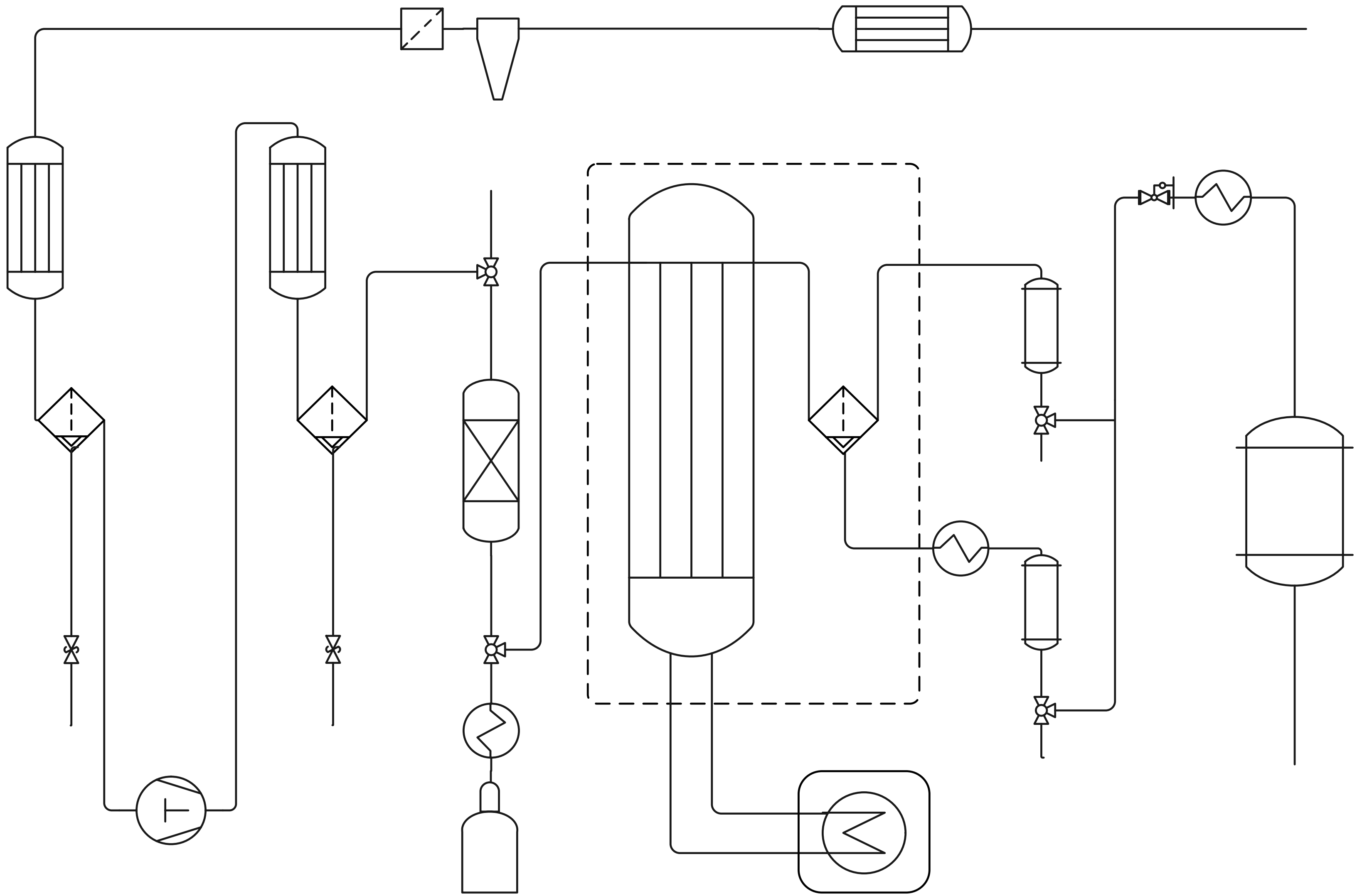
3



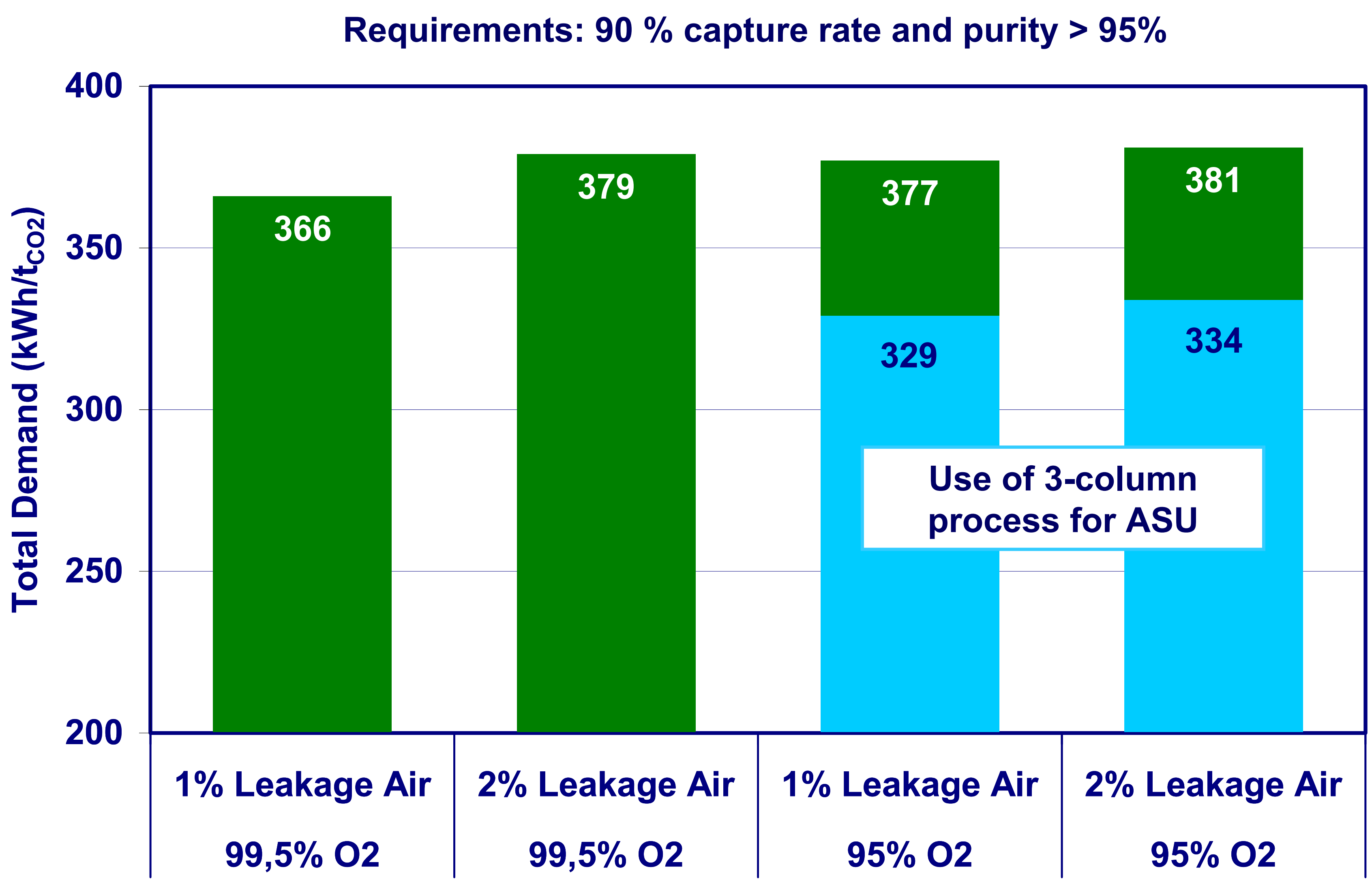
Purity of liquefied CO_2 (in mol-%)

	CO_2	N_2	Ar	O_2	SO_2	NO_x
1	98.4	0.6	0.2	≈ 0.4	≈ 0.4	≈ 470 ppm
2	98.8	0.6	0.2	≈ 0.4	≈ 56 ppm	≈ 47 ppm
3	98.8	0.6	0.2	≈ 0.5	≈ 56 ppm	≈ 22 ppm

Flue Gas Liquefaction Plant

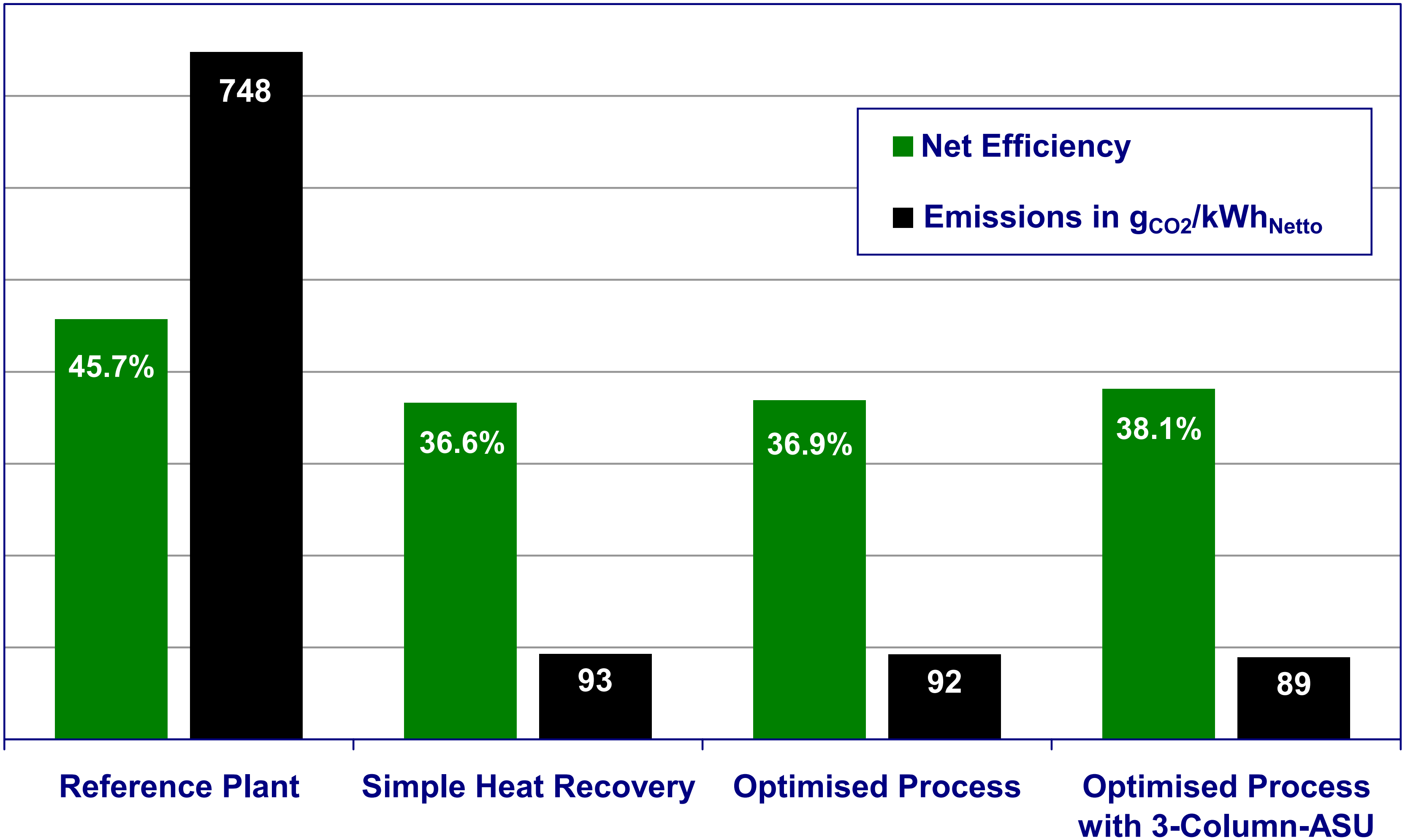


Additional Energy Demand



Comparison of Different Processes
(1% Leakage, Capture Rate 90%, Purity > 98,5%)

TUHH
Technische Universität Hamburg-Harburg



Efficiency of an Oxyfuel Power Plant

- **Underlying reference technology**
  - Reference power plant North-Rhine Westphalia: η = 45.7 % (net)
    power output: 556 MW (net), 600 MW (gross)

- **Key power consumers (based on 600 MW gross power output)**
  - Air Separation Unit:
    ≈ 90 MW to attain 99.5 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 (90 % separation, 1 % leakage air):
    ≈ 47 MW possibly lower due to optimization

- **Estimated efficiency loss:** $\Delta\eta$ = 8 … **10** … 11.5 % abs.

Thank You!

RWTH AACHEN UNIVERSITY

OXYCOAL-AC

Development of a Zero Emission Coal-Fired Power Plant by means of an OTM Air Separation Unit

Hamburg

08.12.2006

S. Engels, Prof. M. Modigell, Prof. R. Kneer, Prof. N. Peters, Prof. R. Abels, Dr. Hönen, Dr. Pfaff

- **Structure of the Research Project**
  - consortium of 6 RWTH-institutes and 5 industrial partners
  - goal: Development of a power plant process, in which the flue gas is as highly concentrated with CO_2 as possible
  - long term project

1. Phase (Sep 2004 to Sep 2007)

➲ Development of power plant components

2. Phase (Sep 2007 to Sep 2010)

➲ Integration of components and testing their functionality and reliability

Companies taking part

- RWE Power AG
- E.ON Energie AG
- Siemens AG
- Linde AG
- WS-Wärmeprozesstechnik GmbH

Institutes RWTH:

- Lehrstuhl für Wärme- und Stoffübertragung
- Institut für Regelungstechnik
- Institut für Werkstoff-anwendungen im Maschinenbau
- Institut für Verfahrenstechnik
- Institut für Strahlantriebe und Turboarbeitsmaschinen
- Institut für Technische Verbrennung

supported by:

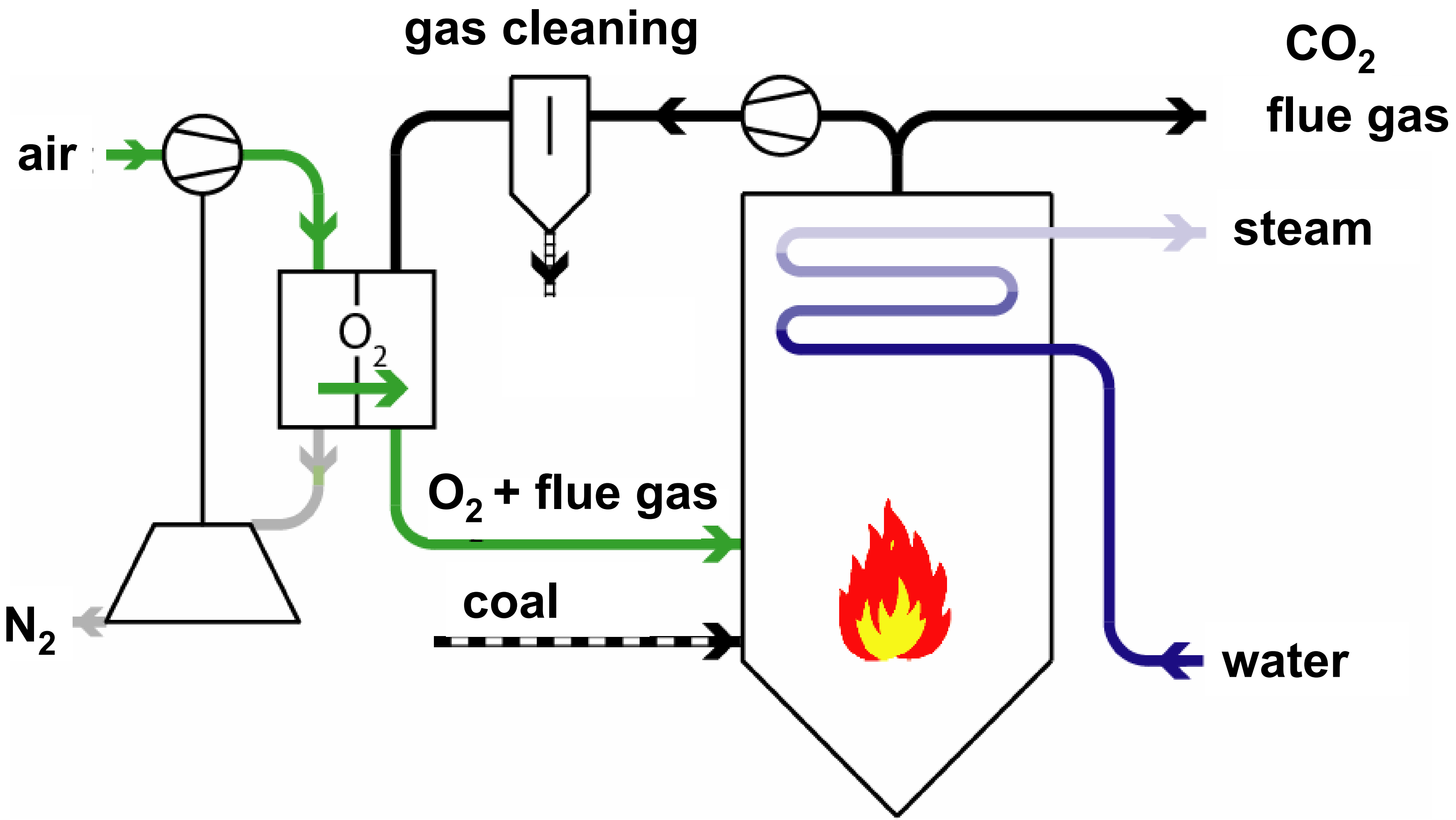
Bundesministerium für Wirtschaft und Technologie

Ministerium für Innovation, Wissenschaft, Forschung und Technologie des Landes Nordrhein-Westfalen

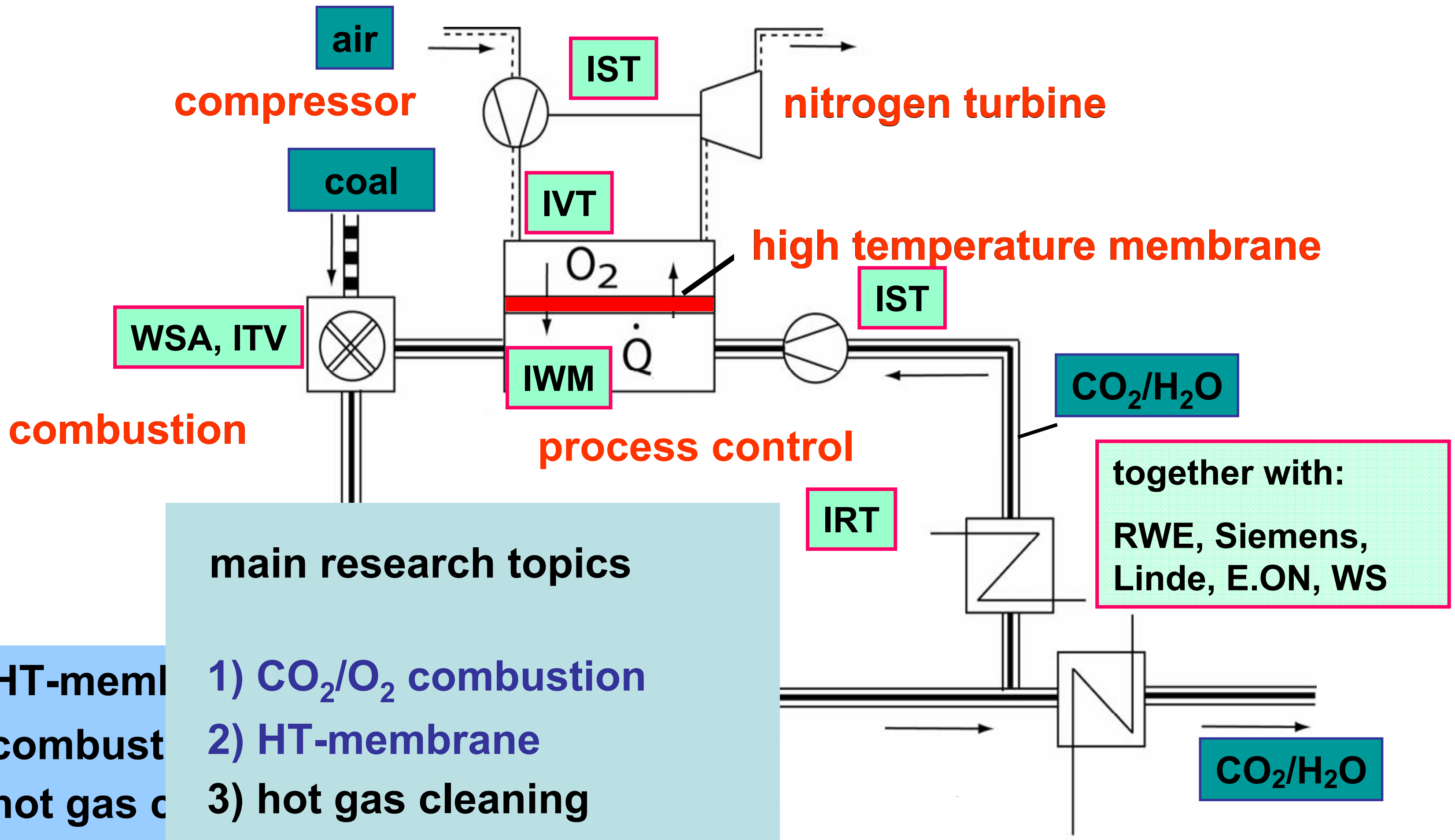
and industrial partners

OXYCOAL-AC Process

efficiency drop: 3-5 % < cryogenic oxyfuel: 8-10 %



Cooperative Project OXYCOAL-AC: Research Topics



together with:

RWE, Siemens, Linde, E.ON, WS

1) HT-meml
2) combust
3) hot gas c
4) turbo co
5) process

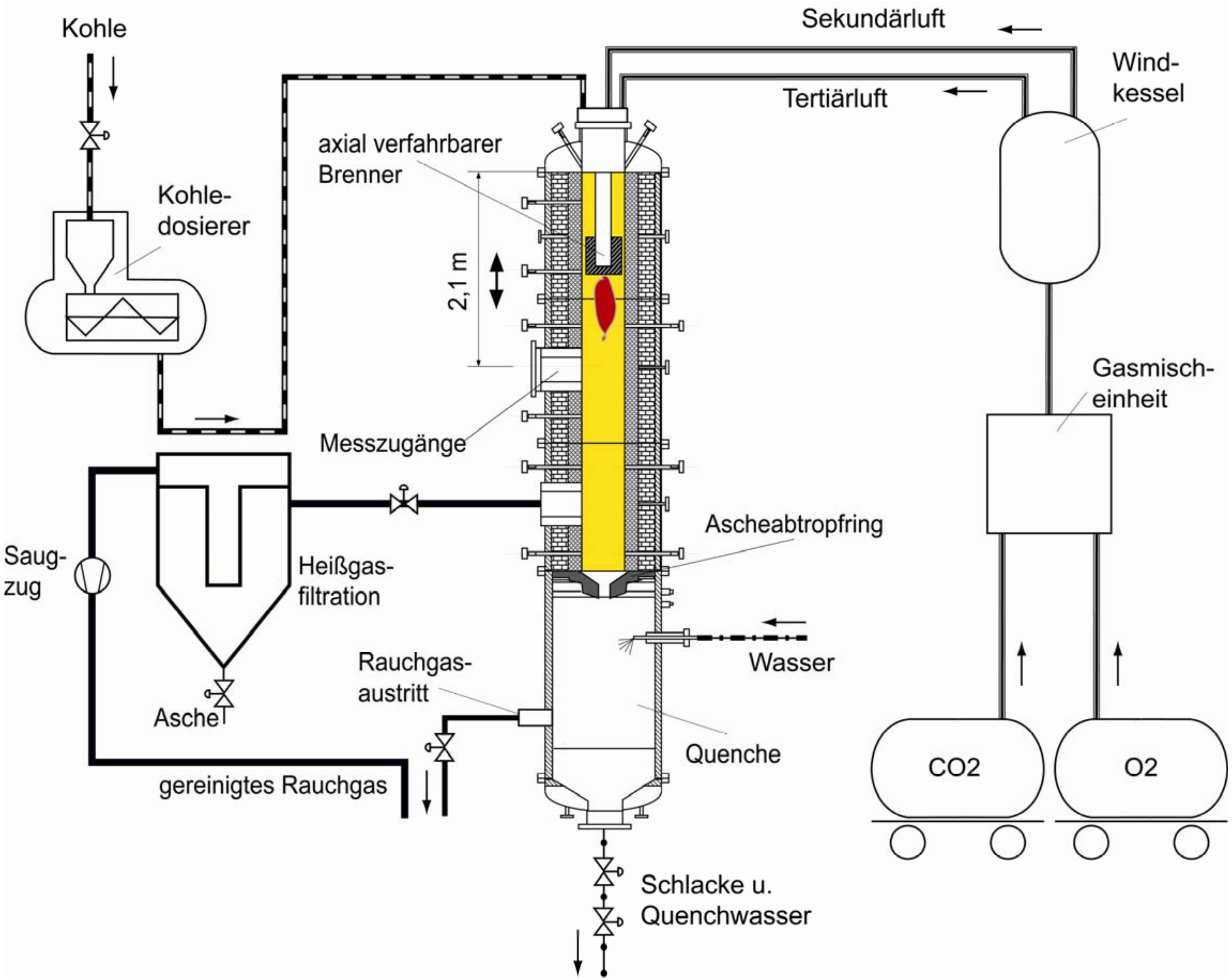
main research topics

1) CO_2/O_2 combustion
2) HT-membrane
3) hot gas cleaning
4) turbo machinery
5) process simulation

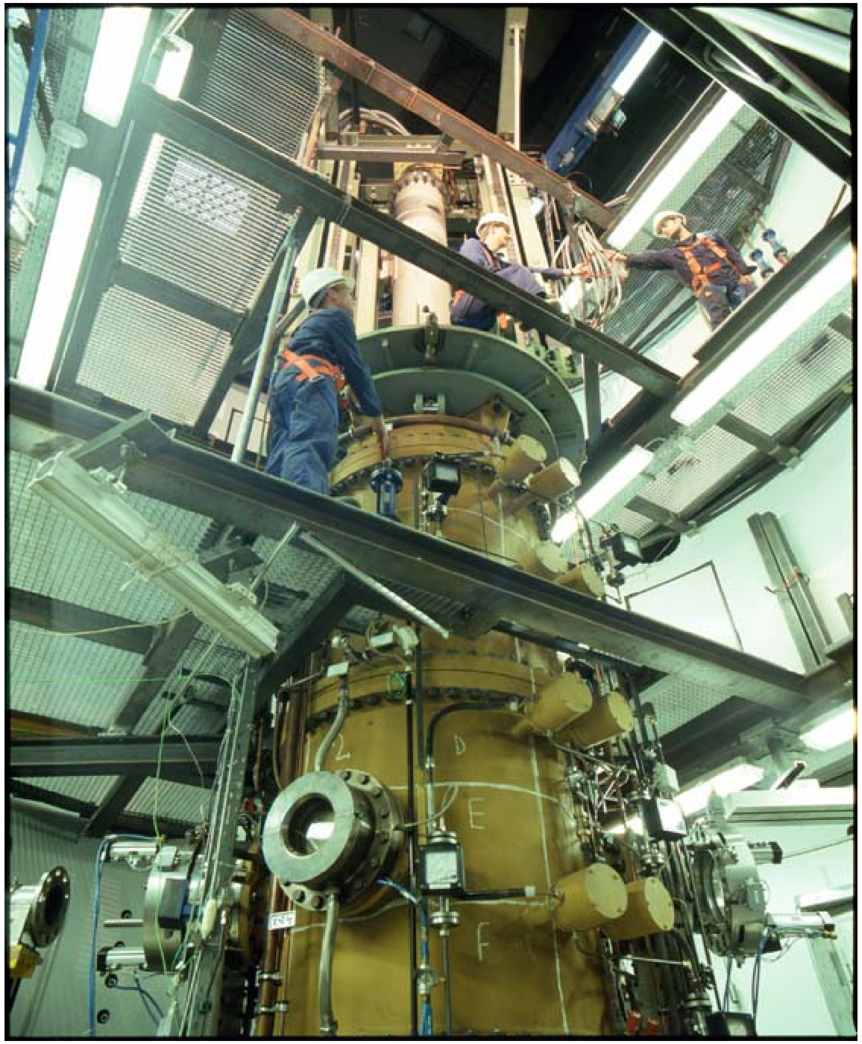
CO_2/O_2 - Combustion

(WSA / ITV)

Experimental Combustor Setup at WSA



Measurement Equipment



Optical Measuring Methods:

particle size:	PDA d > 1µm
gas- und particle-velocity:	LDA PIV
particle temperature:	2 colour-Pyrometer

Sensors:

particle size:	HGPCS
temperature:	thermo couple
gas analysis:	O_2, CO, CO_2, NO_x, SO_2, N_2

Schedule:

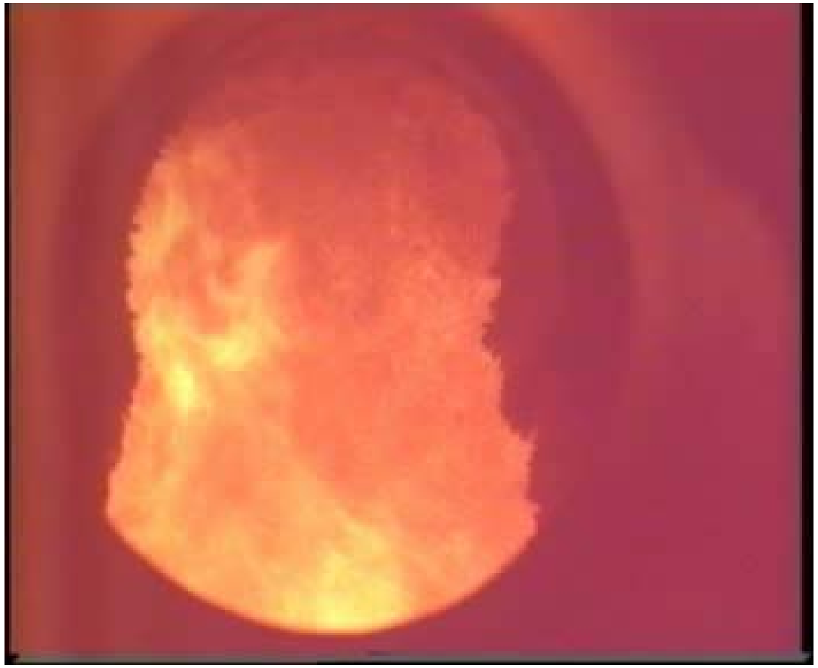
phase 1: operation with external O_2- and CO_2-supply

phase 2: pilot plant (operation with HT air separation unit)

Coal Combustion under OXYCOAL-AC Atmosphere

Development of Burner Geometry with CFD

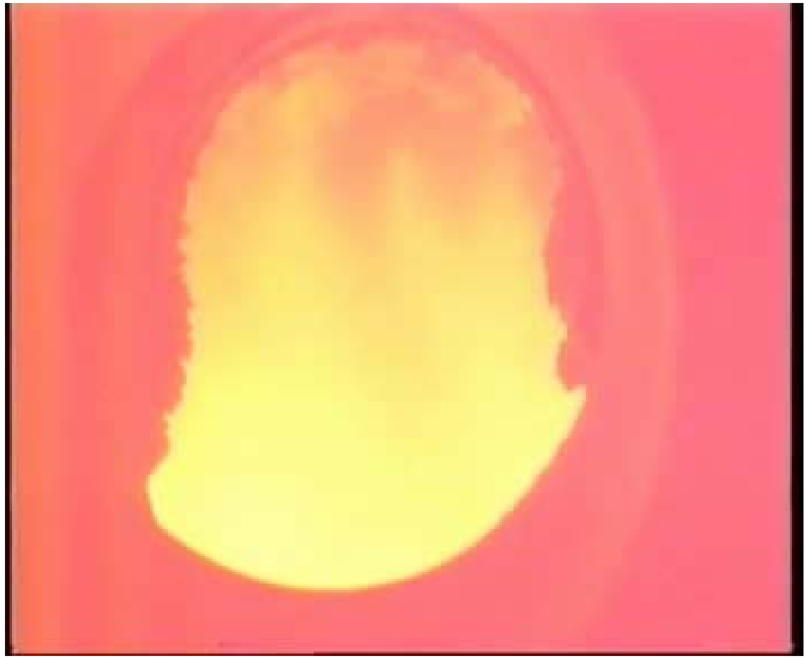
burner 13



$[O_2\,] > 21\%$, rest CO_2

pulsating combustion

burner 15



$[O_2] \sim 21\%$, rest CO_2

stable combustion !!!

Kinetics for the Gaseous Phase of the Coal Combustion

- **Modelling of Kinetics Mechanisms for**
  - Methane (CH4) (the intermediate species appearing during methane oxidation are of interest for the OXYCOAL conditions)
  - NOx (coming from the coal)

➡ **143 elementary reactions, 35 species**

- Development of a reduced reaction mechanism from the detailed kinetics by introducing steady-state assumptions (d[Ci]/dt = 0)

➡ **15 global reactions, 19 species**

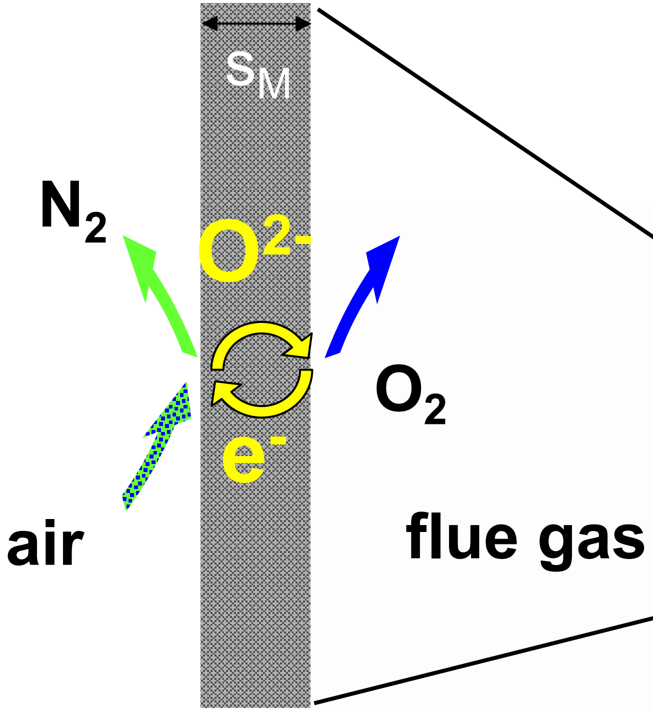
(implementation in CFD code)

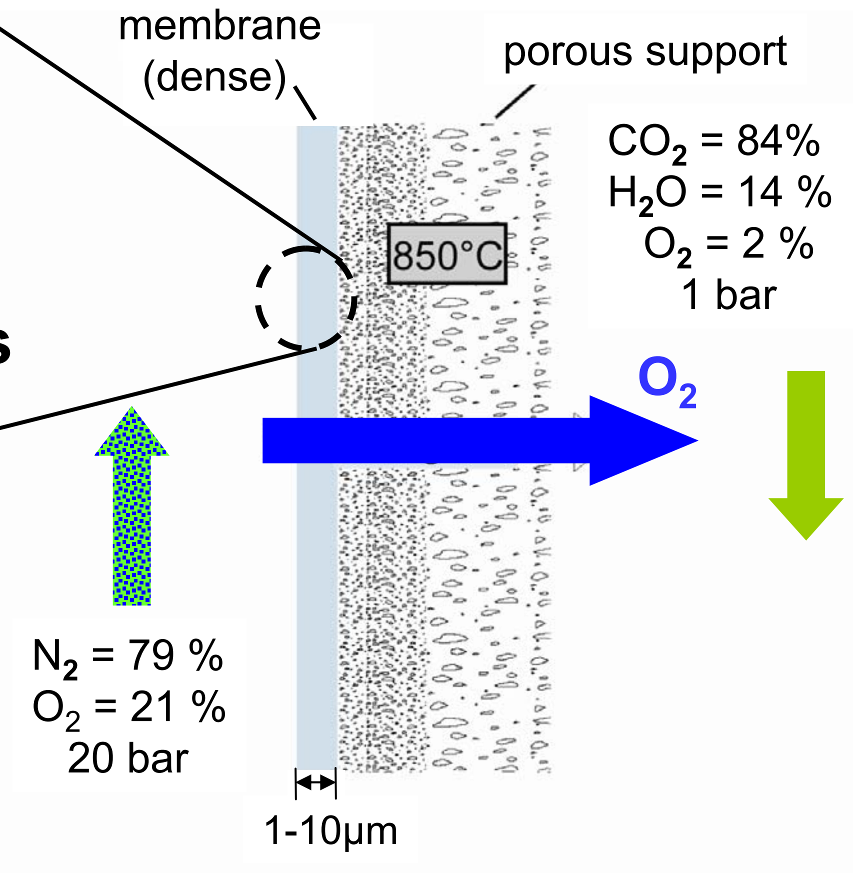
Mixed Ion Electron Conducting (MIEC) Air Separation Unit

(IVT / IWM)

Principle of Atmospheric Oxygen Separation

- active thin **membrane** (perovskite)
- mechanic stability by thick porous **support**





Ion- and electron transport
T>700 °C, 100% selectivity for O_2

$$j''_{O2} = C_W \frac{T_M}{s_M} \exp\left(-\frac{K_W}{T_M}\right) \ln \frac{p_{O2,air}}{p_{O2,fluegas}}$$

Test Membrane Objects

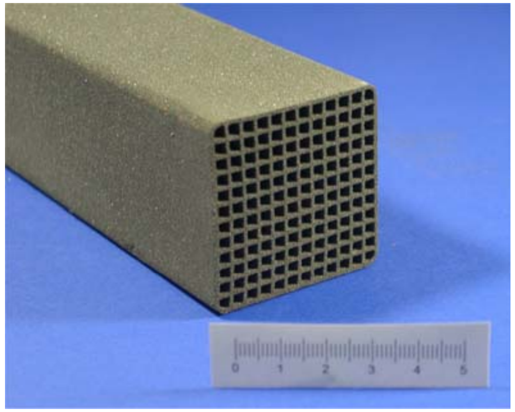
Monolith and Composite Membranes

Perovskite P1: $Sr_{0,5}Ca_{0,5}Mn_{0,9}Fe_{0,1}O_{3-\sigma}$
Perovskite P5: $Ba_{0,5}Sr_{0,5}Co_{0,8}Fe_{0,2}O_{3-\sigma}$

...

monolith tube

composite tube

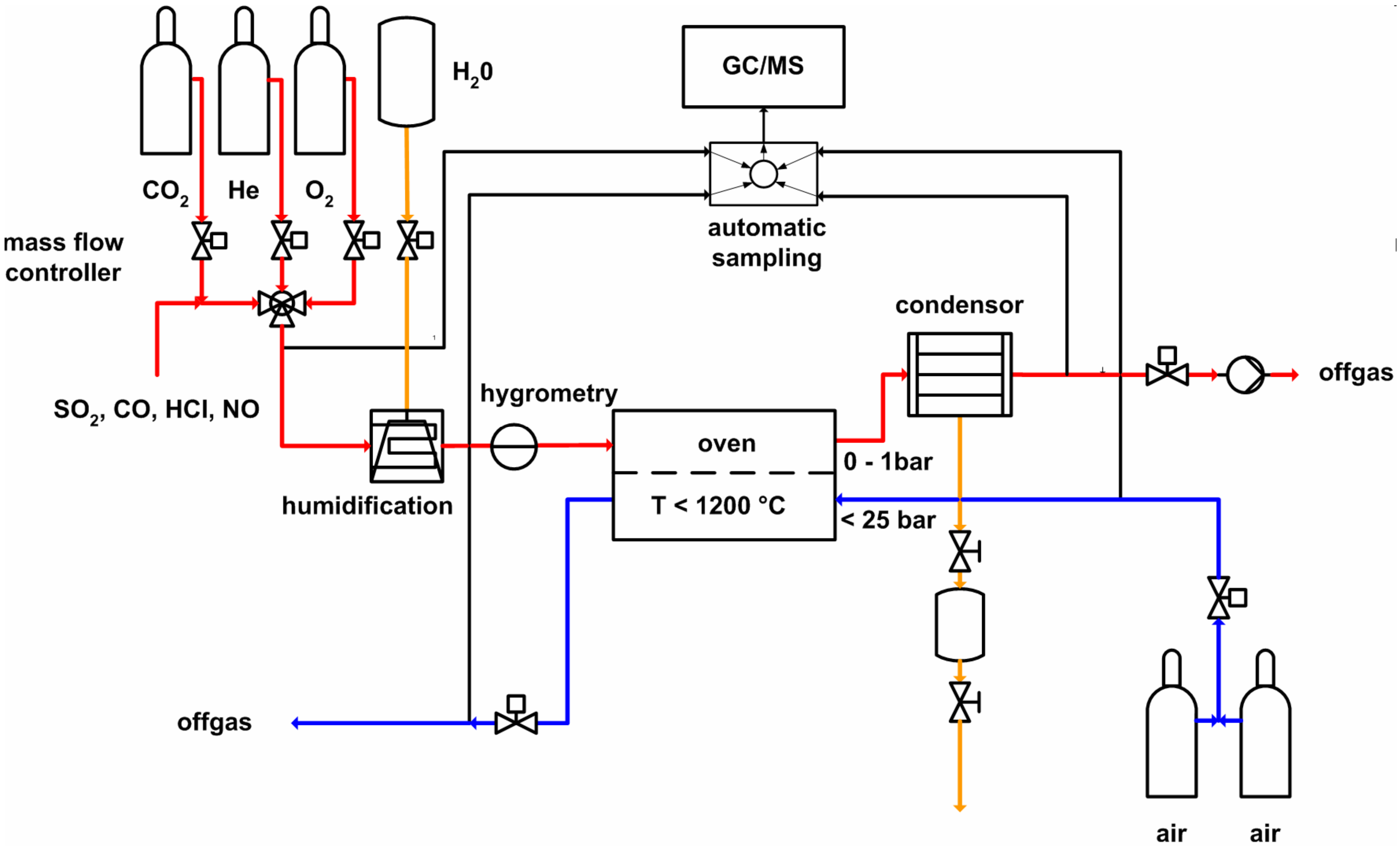


honeycomb

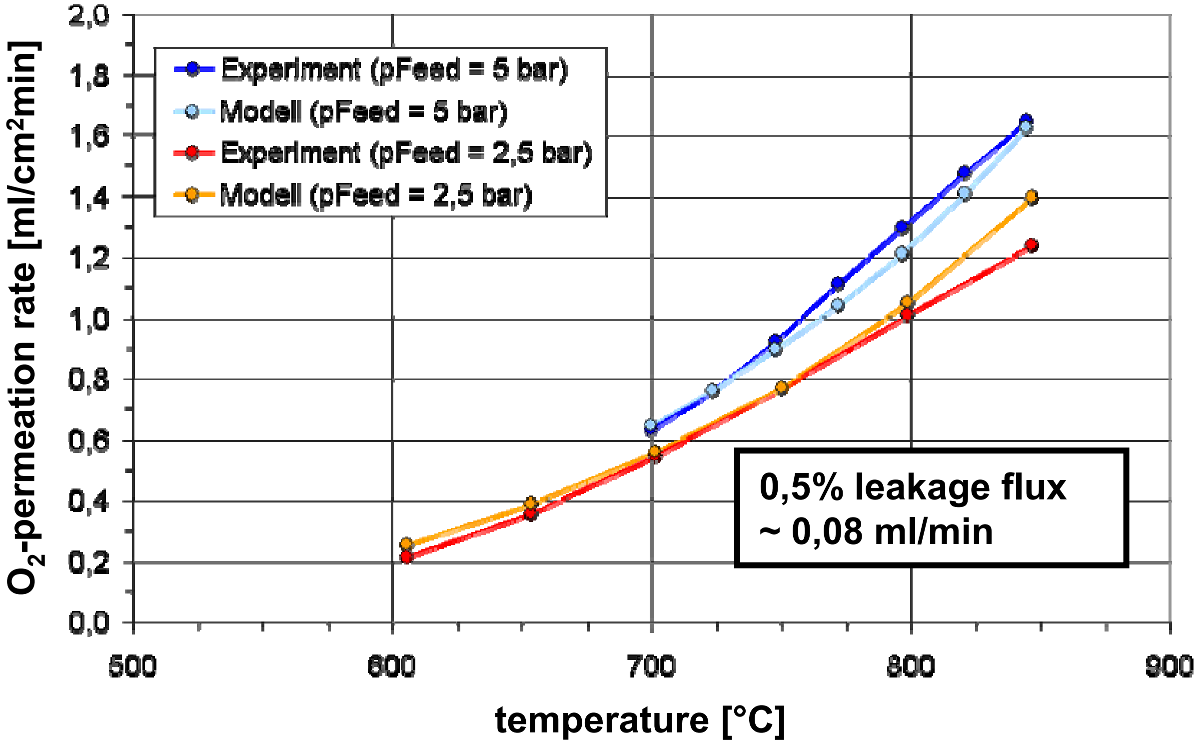
Joining Technology

- Membranes actuated by spring and silver sealing
- Membranes actuated by adhesive bond (brazing)

High Temperature Test Facility for Materials and Modules



Experimental Results of Monolith Perovskites



- average permeation rate under OXYCOAL-AC-conditions (p_{Feed} = 20bar, T_{Mem}=850°C) : **1.9 ml/(cm²*min)** (aim: **3.0 ml/(cm²*min)**)
- an increase in flux is possible by means of thinner membranes (current thickness s_M = 1.07 mm)

Development of Membrane Modules with CFD

		air	flue gas
mass stream	[kg/s]	0,0038	0,0050
T_{inlet}	[K]	1023	1123
pressure	[bar]	20	1
w_{O2} inlet	[gew.%]	0,23	0,03

module geometry

A_{module} : 0,98 m^2

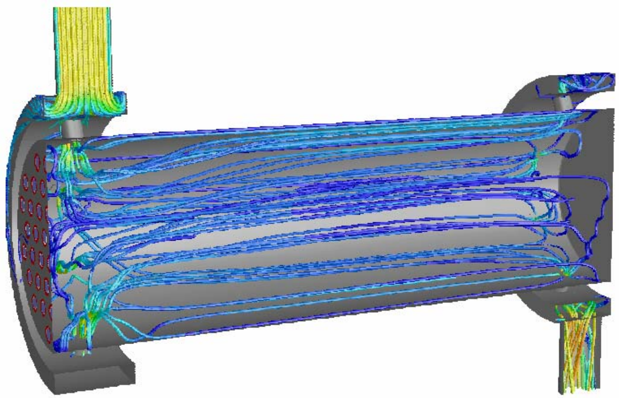
membrane thickness : 1 mm

wagner-equation

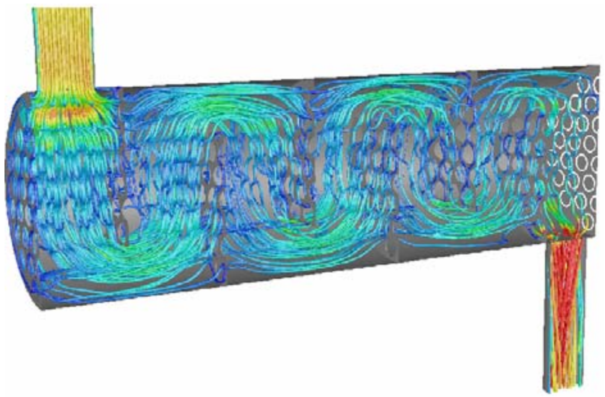
C_{Wagner} : 5,1763e-08 mol/(cm*s*K)

K_{Wagner} : 7200 K

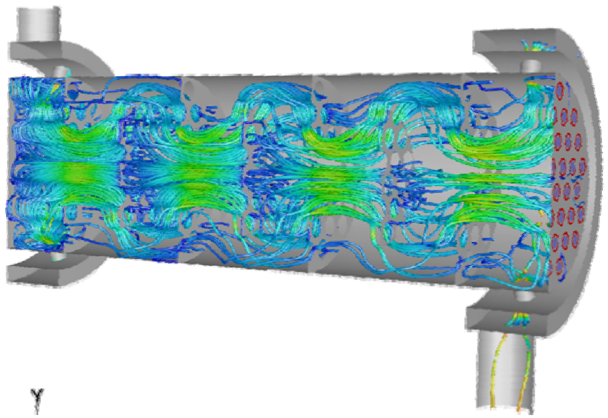
without baffle plates



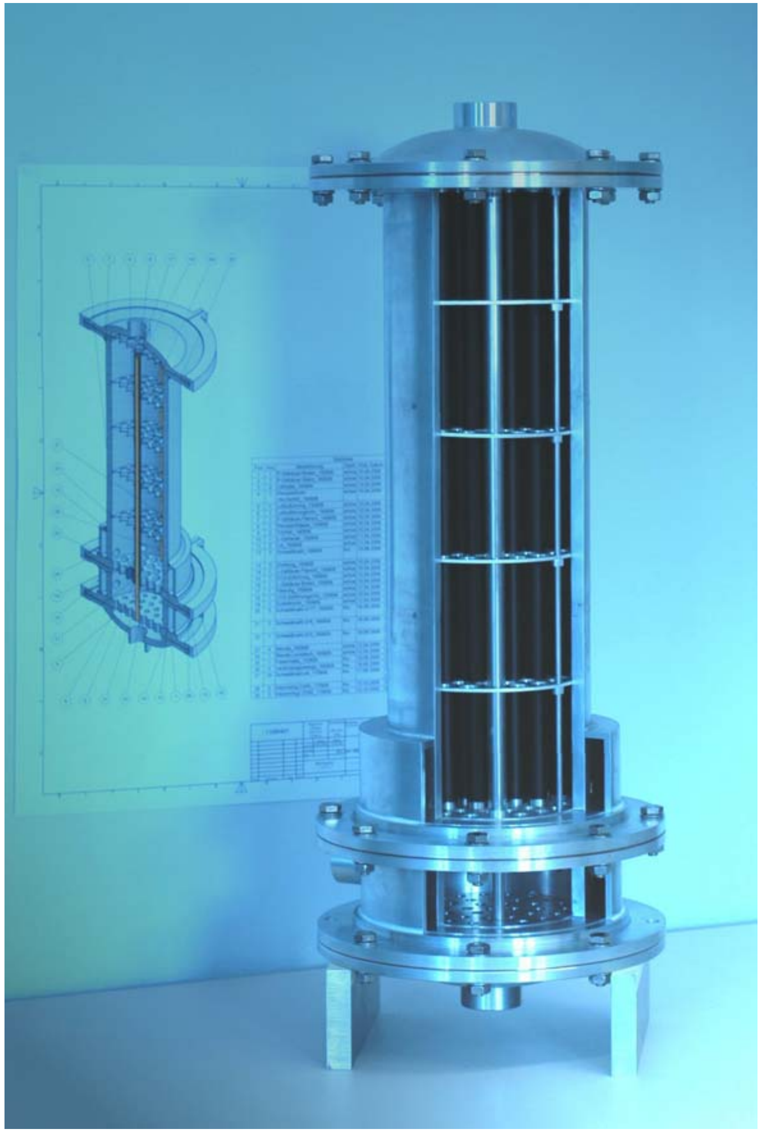
cross flow

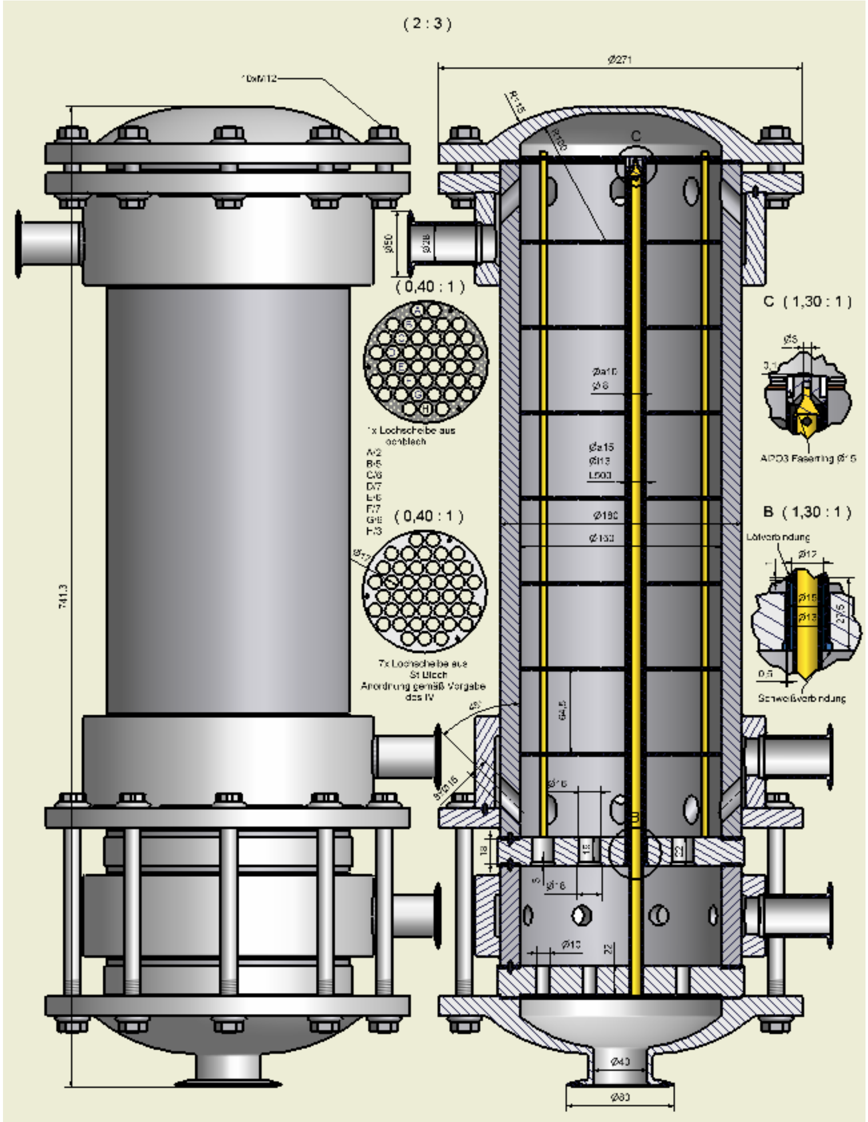


cross flow



Module Design





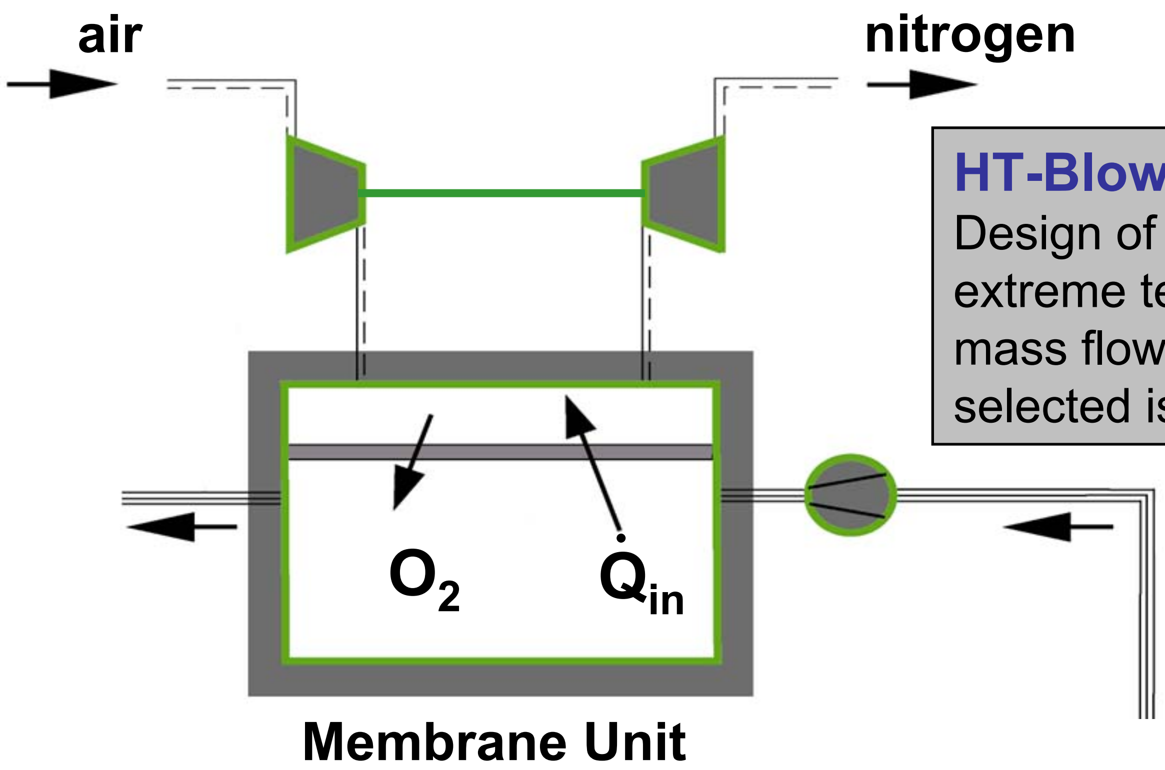
Turbo Machinery:

Air Compressor,
Nitrogen Turbine,
HT-Blower

(IST)

Tasks and Objectives of the IST

Air Compressor and Nitrogen Turbine
Select a design, define the components, study turbine/compressor linking, investigate behavior in start up, shut down, full-/ part load, compile concepts for automatic control



HT-Blower
Design of critical components for extreme temperatures and high mass flows (consideration of selected issues)

Process Simulation

(WSA / IRT / IVT / IST)

Process Simulation

Stationary Simulation

- optimisation of overall efficiency
- thermochemical behavior of minor components
- turbo machinery
- software: Ebsilon®
AspenPlus® / ChemApp®
IPSEpro®

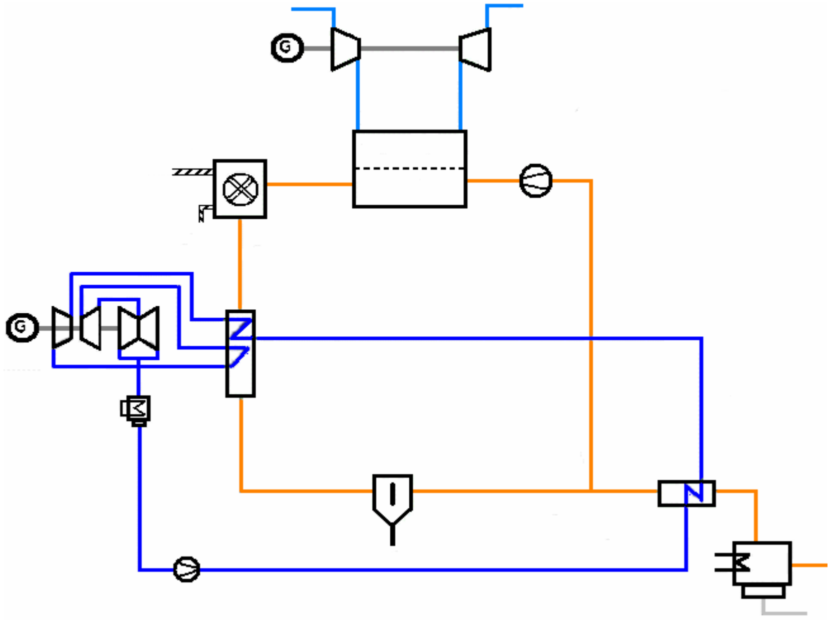
Dynamic Simulation

- start up / shut down
- control concepts and parameters
- software: Modelica / Dymola®
Matlab® / Simulink®

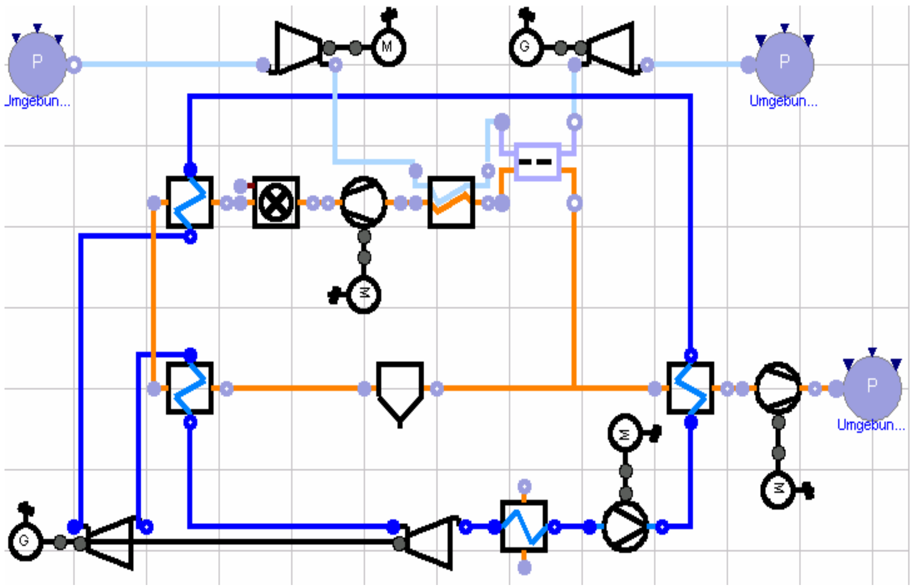
Dynamic Process Modelling

- Process control requires a dynamic process model
- An object oriented, physics based modelling approach using the Modelica language is realised

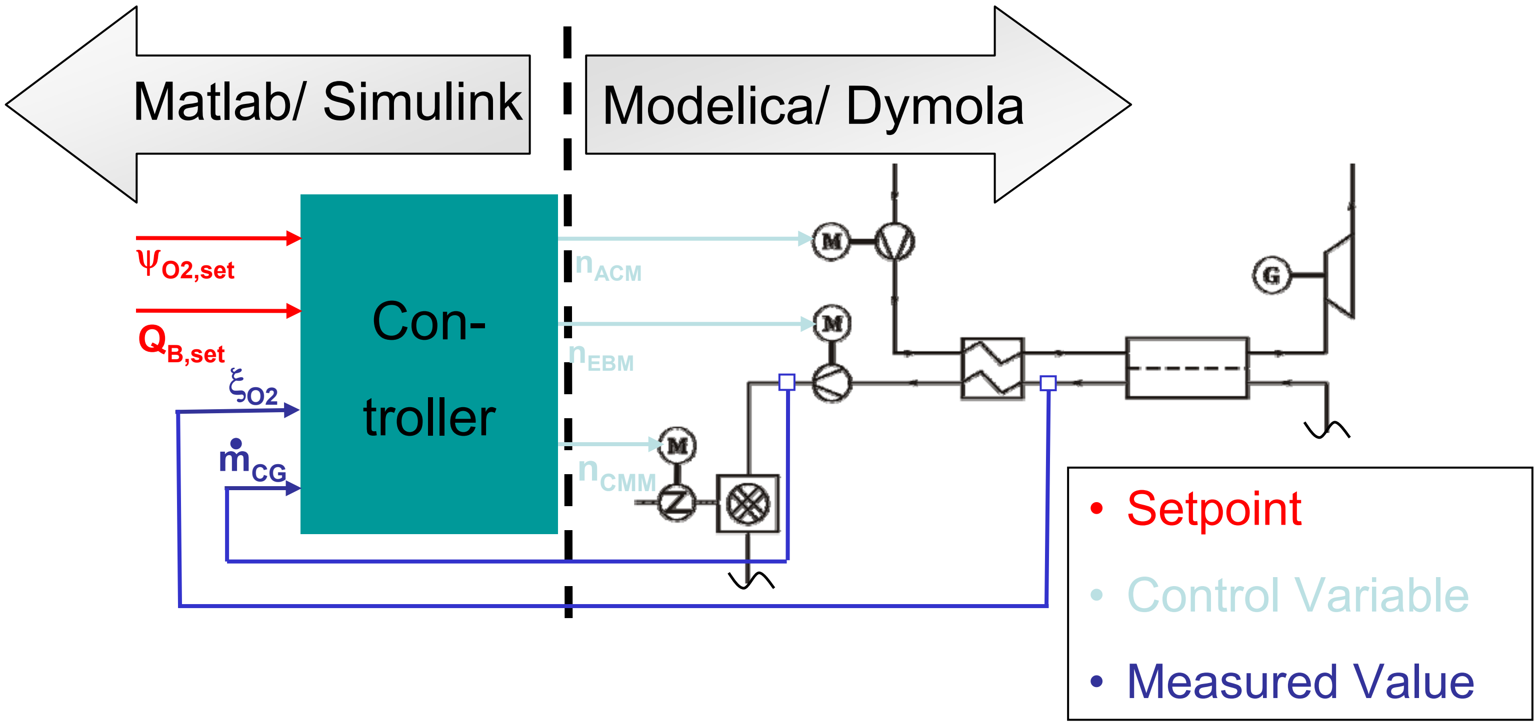
Process



Process Model

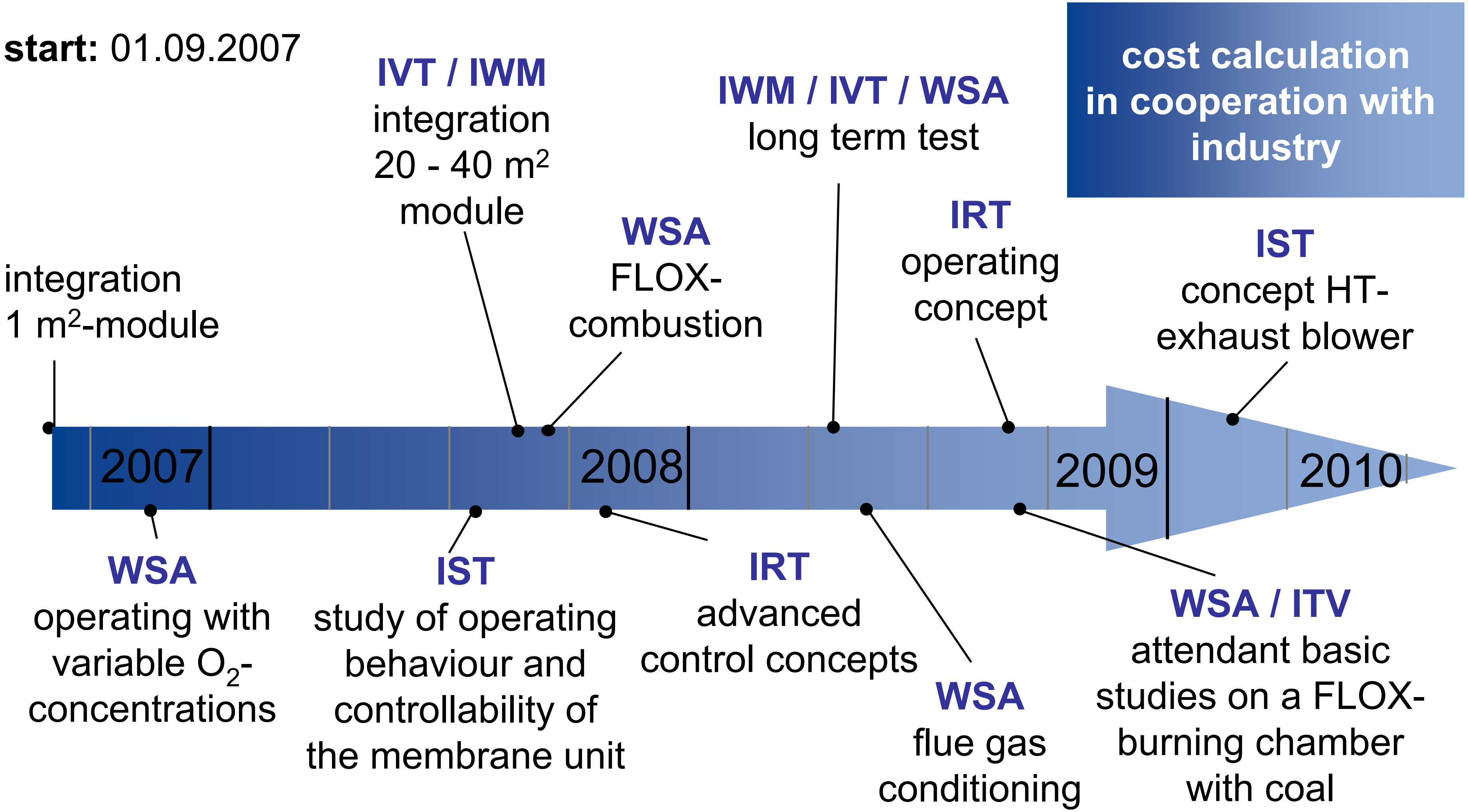


Example of a Control Loop

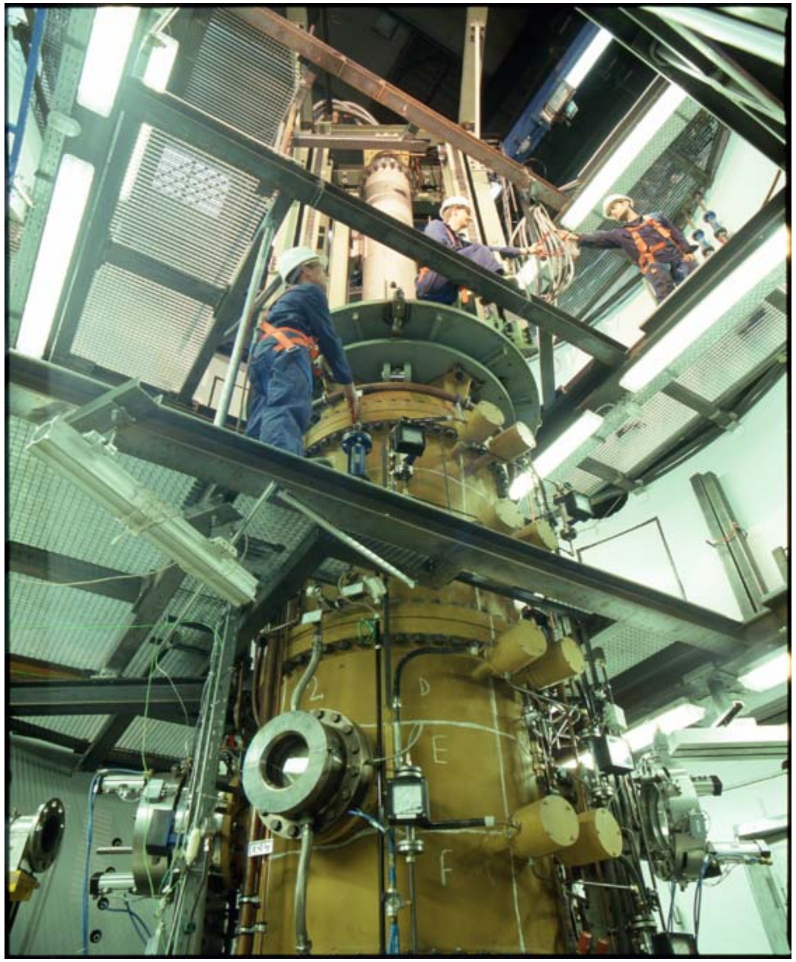


Control of the combustion gas mass flow and the oxygen mass fraction by the rotational speed of the compressor and the exhaust blower

Future Work


start: 01.09.2007
cost calculation in cooperation with industry
integration 1 m²-module
IVT / IWM
integration 20 - 40 m² module
WSA
FLOX-combustion
IWM / IVT / WSA
long term test
IRT
operating concept
IST
concept HT-exhaust blower
2007
2008
2009
2010
WSA
operating with variable O_2-concentrations
IST
study of operating behaviour and controllability of the membrane unit
IRT
advanced control concepts
WSA
flue gas conditioning
WSA / ITV
attendant basic studies on a FLOX-burning chamber with coal

Thank you for your attention!



WSA-pilot-plant (120 kW_{th})

TECHNISCHE UNIVERSITÄT DRESDEN

Faculty of Mechanical Engineering, Institut for Energy Technology, Chair for Power Plant Technology

Stefan Hellfritsch

Research on Oxyfuel Technology for CO_2 separation from coal-fired power plants

Activities at TU Dresden

Developments in Oxy-Combustion Technology for CCS Power Plants
IEA Young Researchers Forum
Hamburg University of Technology, 8 December 2006

TECHNISCHE UNIVERSITÄT DRESDEN

Outline of presentation

1. History of Oxyfuel-related research at TU Dresden
2. Introducing the $50kW_{th}$ Oxyfuel combustion test facility
3. Pulverised coal burner development for Oxyfuel using CFD
4. Operational experience and first combustion test results
5. Oxyfuel boiler optimisation
6. Research activities on Oxyfuel flue gas treatment
7. Design and assessment of an Oxyfuel power plant process for lignite with CO_2 separation

History of Oxyfuel-related research activities at TU Dresden

09/2003 Study on a lignite-fired Oxyfuel power plant wit CCS based on one of the Lippendorf units (933 MW_{el} each)

10/2003 Planning an Oxyfuel retrofit for the existing 50 kW_{th} pulverised-coal combustion test facility

06/2004 Handing in the proposal for the ADECOS project
→ 3 universities, 6 industrial partners
→ budget: 3.1 Mio. Euro (~66% by BMWi)
→ project co-ordination: TU Dresden

07/2004 Study on a 15 MW_{th} Oxyfuel boiler for a possible pilot plant

12/2004 Study on a 300 MW_{el} ASC Oxyfuel boiler for pre-dried lignite

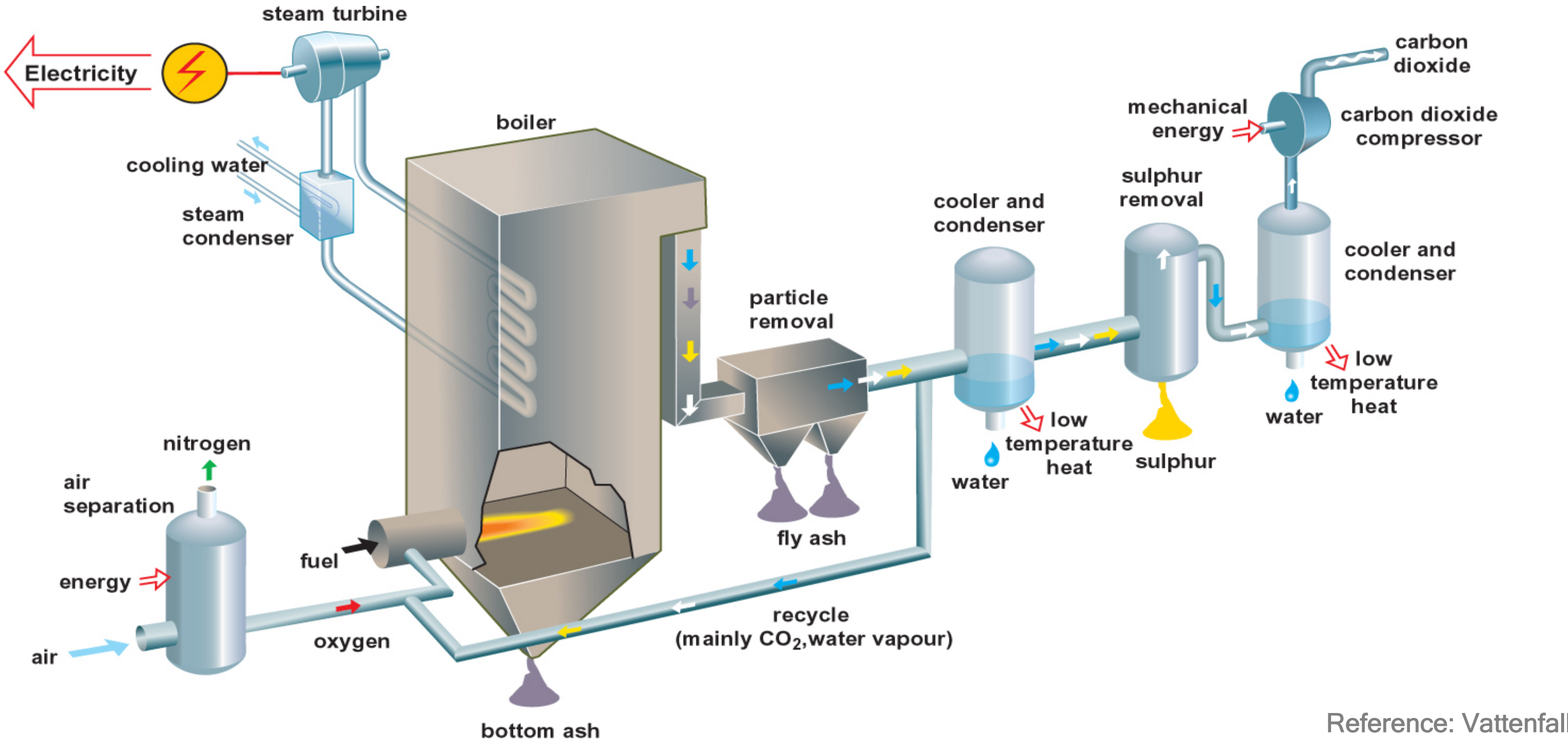
06/2005 ADECOS Kick-off meeting

03/2006 Commisioning of the 50 kW_{th} Oxyfuel combustion test facility

08/2006 Commisioning of the wet desulphurisation test rig

09/2006 ADECOS Phase II
→ including distillation as possible $DeSO_x$ process
→ new topic: operational flexibility of Oxyfuel power plants

Identified key topics for Oxyfuel-R&D



Reference: Vattenfall

→ **Boiler is the dominant change compared to conventional power plants**

→ **Flue gas treatment / CO_2 purification is challenging**

→ **Overall process has to be designed, optimised and evaluated**

ADECOS project partners

Advanced Development of the Coal-fired Oxyfuel Process with CO_2 separation

TECHNISCHE UNIVERSITÄT DRESDEN

Chair for Power Plant Technology
project co-ordinator

VATTENFALL

Vattenfall Europe Generation AG & Co. KG

RWE

RWE Power AG

TUHH Technische Universität Hamburg-Harburg

Institute of Energy Systems
Institute of Thermal Separation Processes

Hochschule Zittau / Görlitz (FH)
University of Applied Sciences

Institute of Process Technology, Process Automation and Measuring Technology

ALSTOM

Alstom Power Boiler GmbH

e·on Energie

E.ON Energie AG

Federal Ministry of Economics and Technology

SIEMENS

Siemens AG Power Generation

HITACHI Inspire the Next

Hitachi Power Europe GmbH

www.adecos.de

ADECOS – Main tasks

- Oxyfuel combustion tests for different coals and CFD simulation
- Boiler optimisation and technical evaluation (flue gas recirculation, oxygen feed, security, operation procedures)
- Assessment of alternative boiler types for Oxyfuel (circulating fluidised bed, slag tap furnace)
- Design of the CO_2 recovery train, assessment of different types of desulphurisation systems
- Integration of the required additional plant components into the power process and combined optimisation.

➔ **Process Evaluation: show technical and economic feasibility under near-term conditions (e.g. CO_2 tax)**

TECHNISCHE UNIVERSITÄT DRESDEN

50 kW_{th} Oxyfuel combustion test facility for pulverised coal

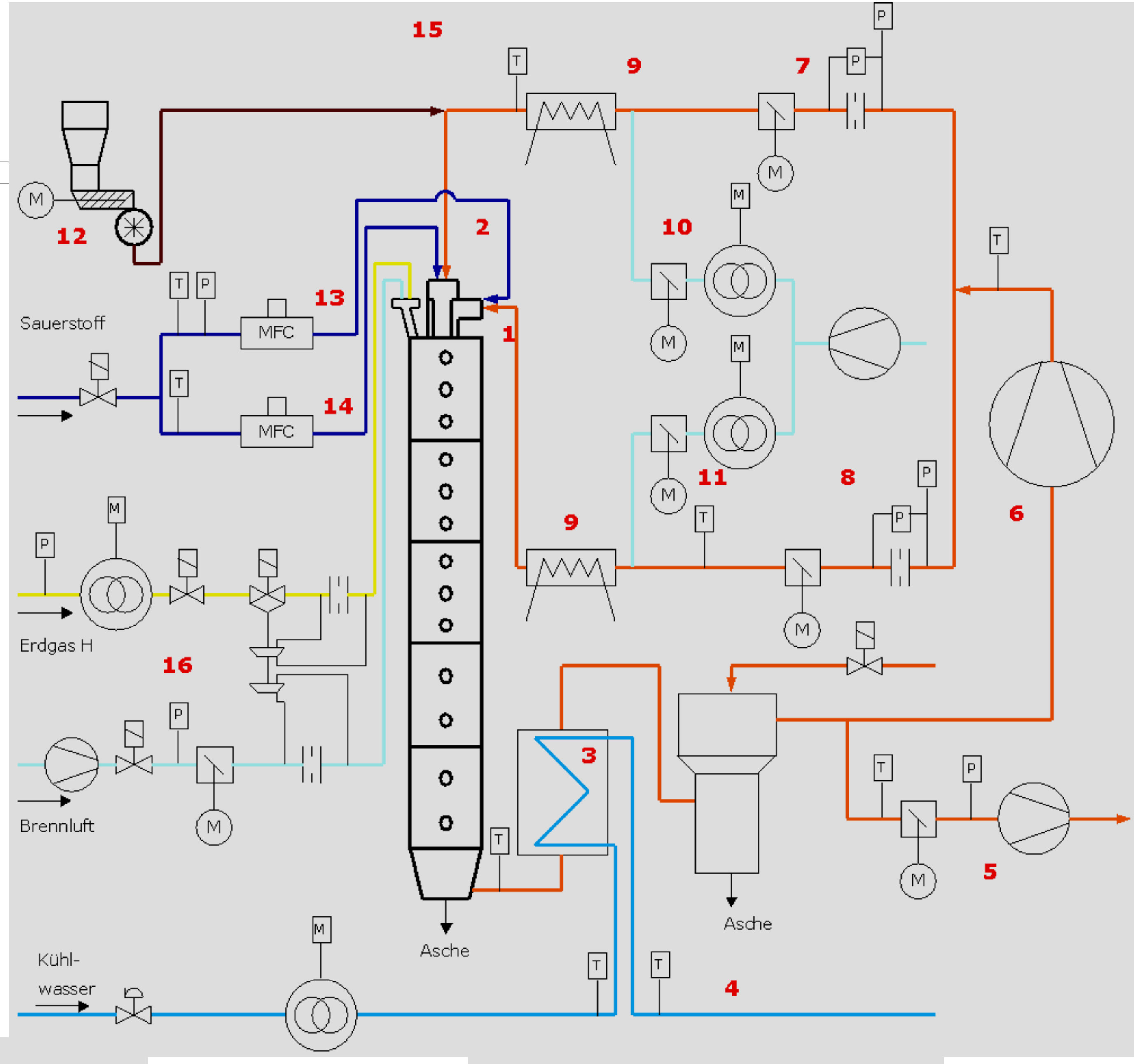
Main parameters

Thermal input	50 – 60 kW
Combustion chamber dimensions	∅0,29 x 2,5 m
pre-dried lignite feed rt. (~10 % water content)	6 – 12 kg / h
Oxygen feed rate	0 – 20 kg / h
flue gas recycle	20 – 80 kg / h
feed gas temperature (air, recycled flue gas)	100 – 400 °C

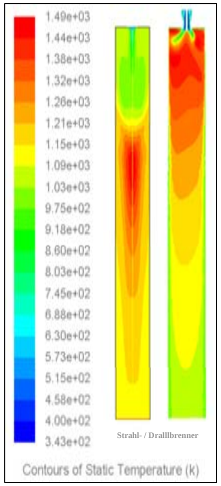
Measurement and analysis

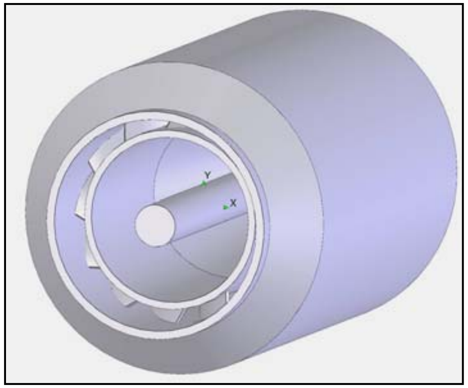
- flue gas composition (CO_2, CO, O_2, SO_2, NO, Humidity)
- ash & slag analysis
- slag depositon rate on special probes

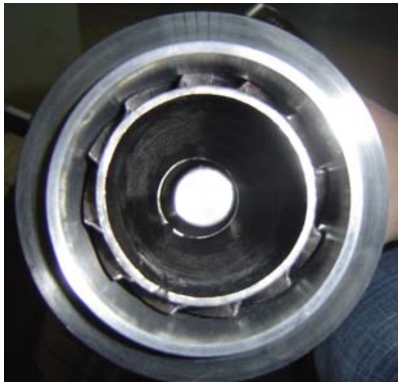
50 kW_{th} Oxyfuel combustion test facility - Process flow scheme

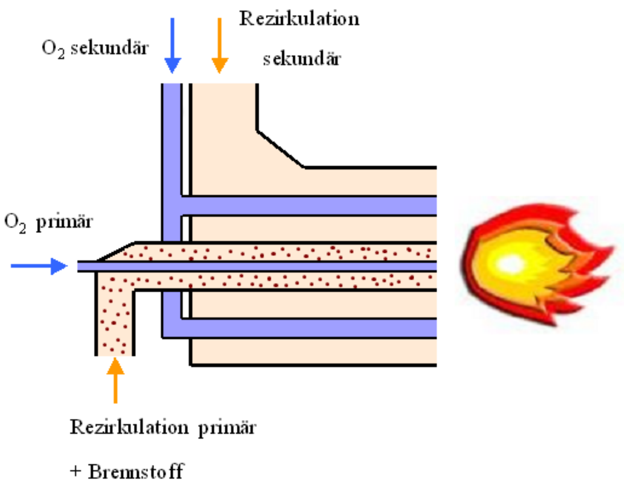


Oxyfuel burner for pulverised coal – optimisation by using CFD





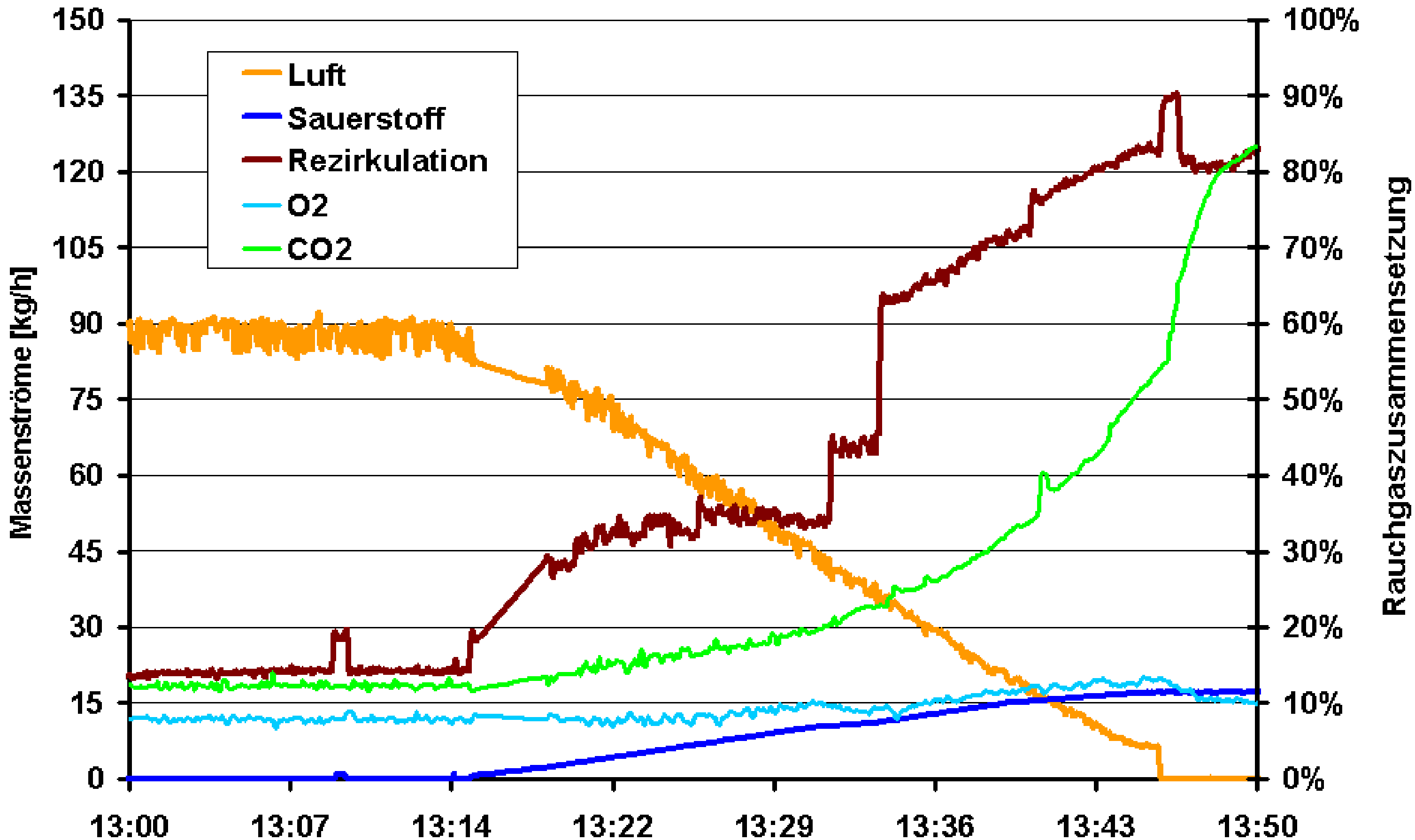




- Original jet burner design caused unstable combustion (lifted flame) and low burnout rate
- Re-design using CFD (FLUENT 6)
- New swirl burner features premixing of oxygen with recycle gas
- Central oxygen lance temporarily closed
- Cross-sections and velocity profiles optimised for faster ignition

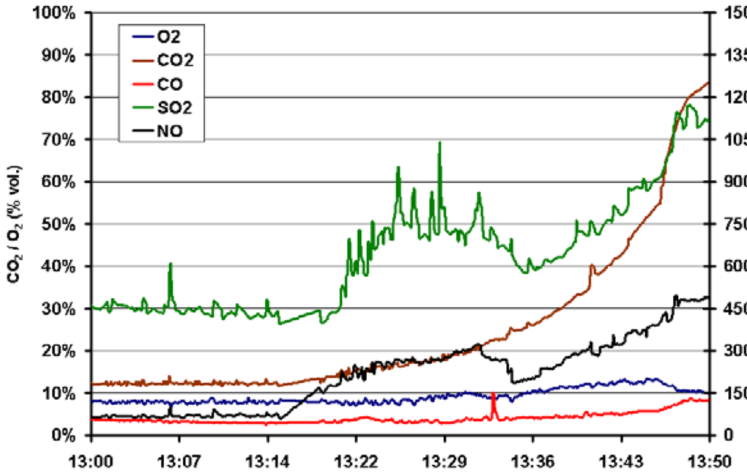
→ **Stable flame close to the burner**

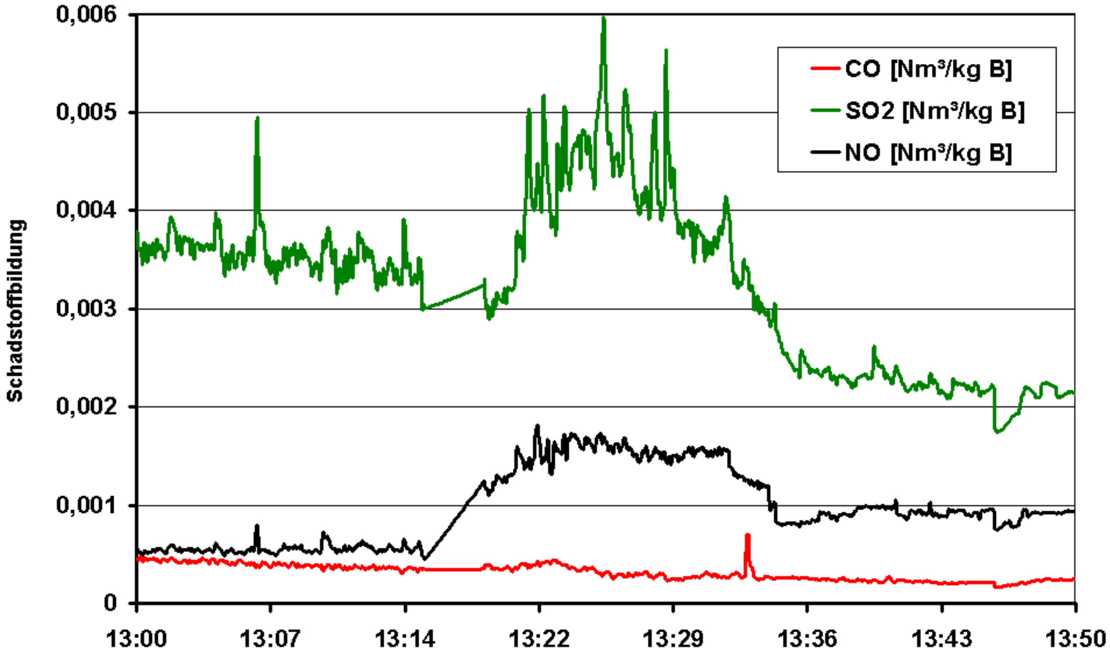
First results – transition behaviour



- Transition from air-blown combustion to oxyfuel mode
- constant oxygen concentration at the burner (17,5%), similar velocities

Comparing air-blown and oxyfuel combustion – first conclusions





- Oxyfuel flame is located closer to the burner and more compact in shape. Increasing oxygen concentration emphasises this effect.

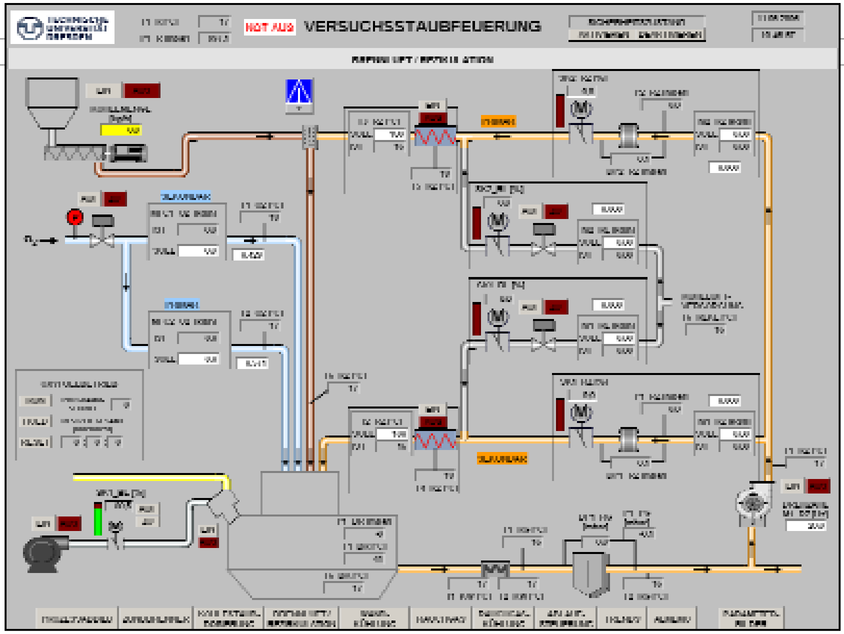
→ **Reaction kinetics changed, to be further investigated by CFD.**

- Specific amount of pollutants seems to decrease except for NO.

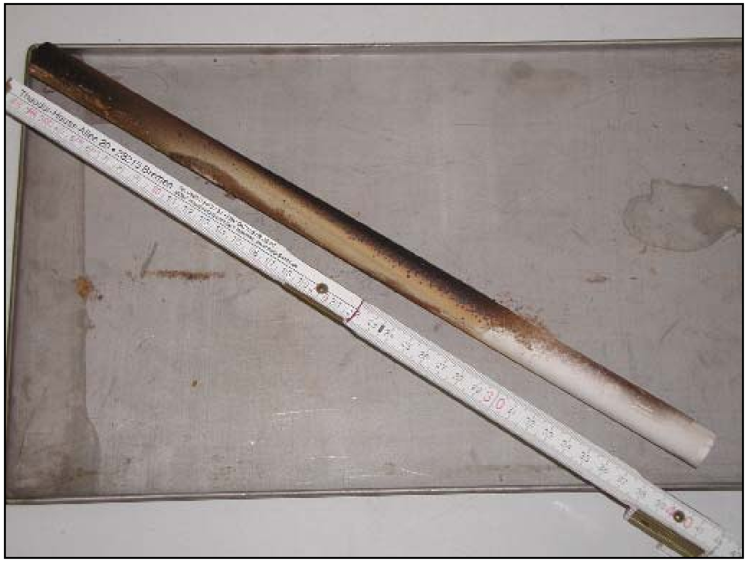
→ **Systematic investigation of pollutant build-up will follow, including NO_x control mechanisms.**

Plant control, probing systems

- Control over the plant by graphical user interface (ProTool Pro) with SPS S7
- Time step programming for smooth transition from one mode to another



Main control sheet

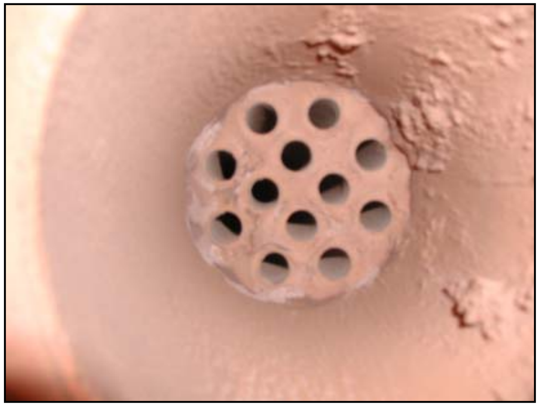


Slag deposition probe (after 3:20 hr)

- Insertion and removal of probes without air ingress → special probing ports with ball valves and sealing system
- Currently in use: Particle extraction probe, uncooled temperature probe and slag deposition probe
- Special cooled suction probe with temperature sensor under construction

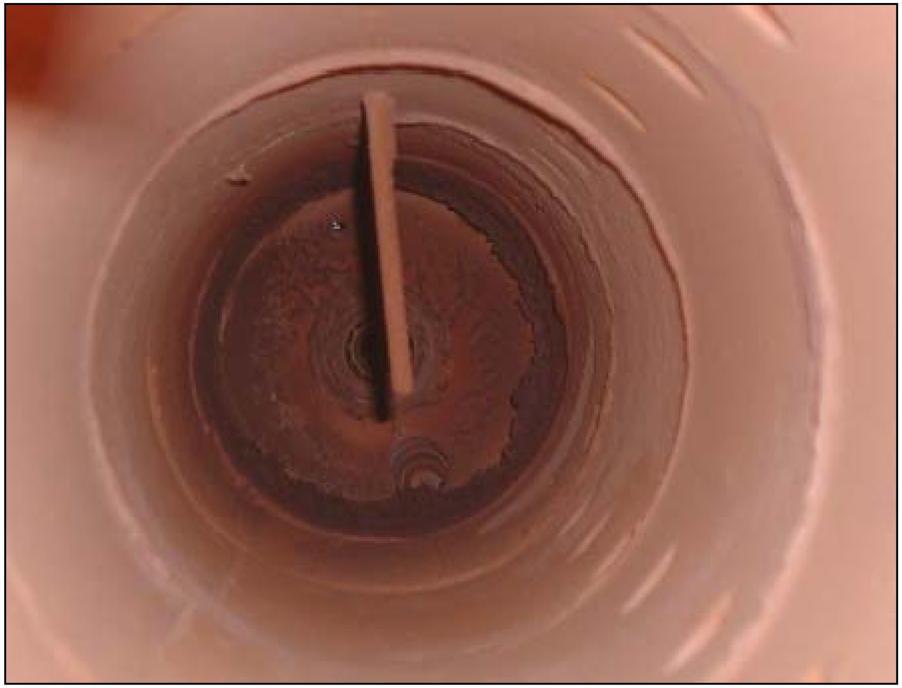
Other operational experience

- Smooth and easy operability of the plant
- Rather short transition times air-blown to oxyfuel (<15 minutes still possible)
- No agglomeration effects detected in the primary stream
  → **Pulverised coal can be transported with wet recycled oxyfuel flue gas**
- Condensate from flue gas with low pH
  → **Need to be careful with low temp.**
- Swirl burner is the choice for small-scale combustion of pulverised fuel – no slagging though



Hot-tube heat exchanger

Upward view into combustion chamber

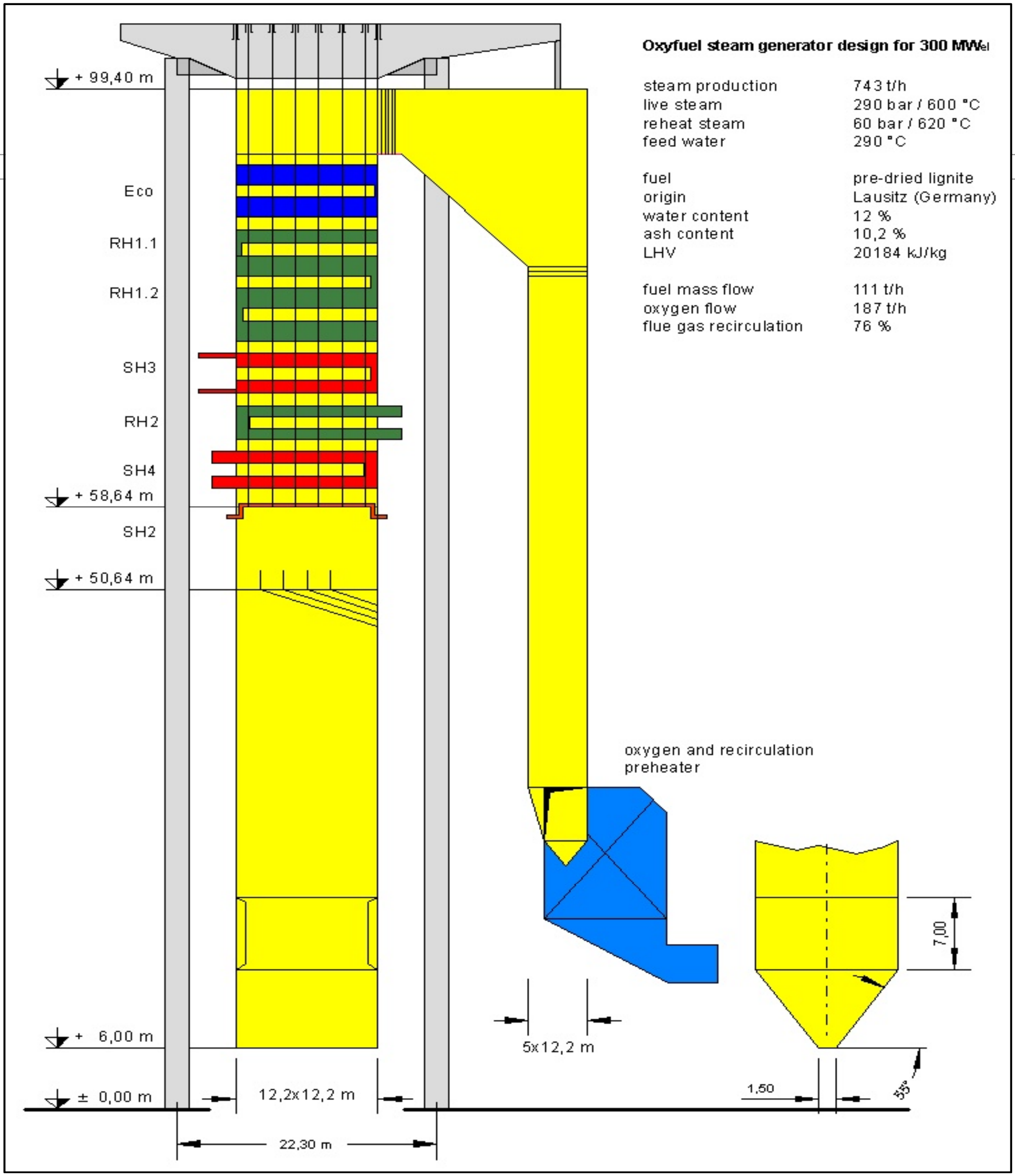


Oxyfuel boiler development

- Design study for a PC Oxyfuel boiler by TU Dresden (2004)
- Matches a 300 MW_{el} concept
- Advanced supercritical steam parameters
- Features preheating of oxygen and recycled flue gas

→ **Rather slim shape as compared to a conventional unit fired on raw lignite.**

- ADECOS: Design for 1000 MW_{el} and comparison with slag-tap furnace and circulating fluidised bed systems



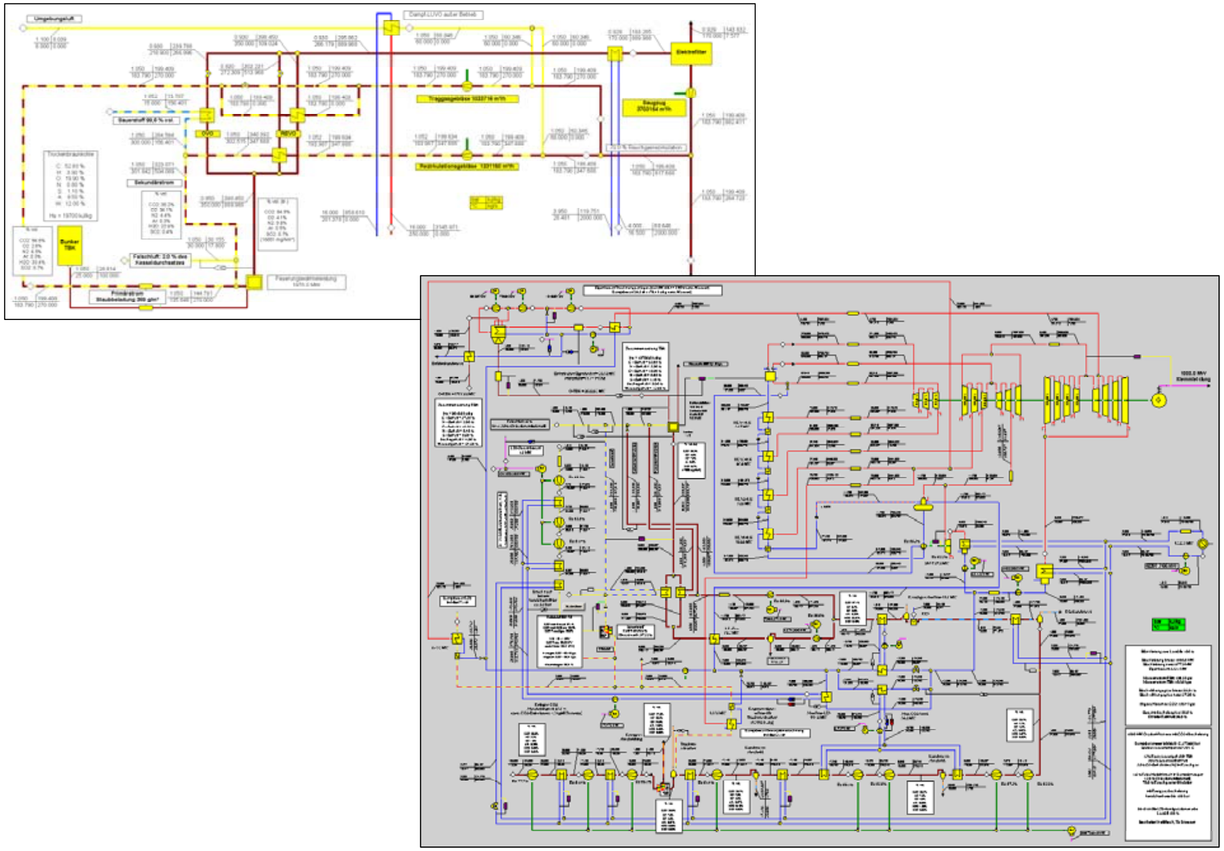
Oxyfuel flue gas treatment / $DeSO_x$

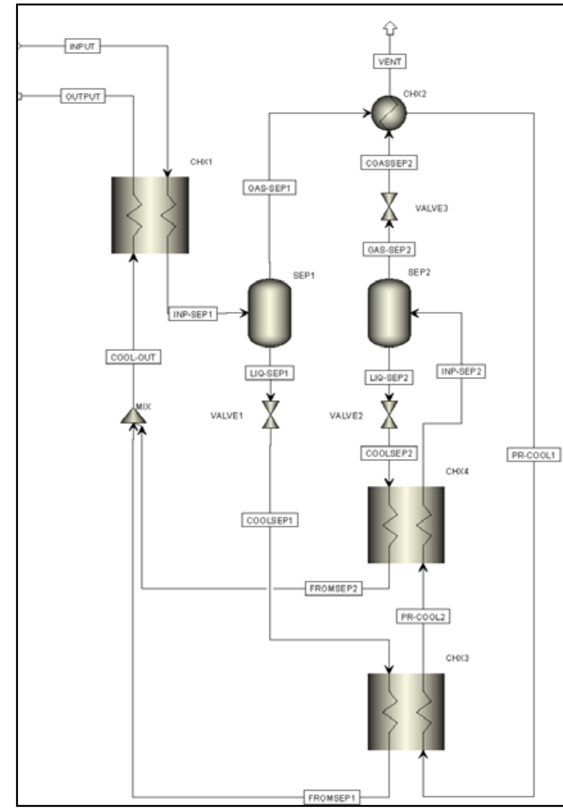
- Test rig for wet desulphurisation processes connected to the 50 kW_{th} combustion test facility
- Broad variety of parameters adjustable (pH, liquid/gas ratio, gas flow, particle content of the suspension, absorber height)
- Can be used as a double-cycle unit or like a bubble-jet system

- Distillation is a promising technology for oxyfuel flue gas $DeSO_x$ and inherent inerts removal
- Easy integration into existing compression chain. Problem of high SO_2 level in first compression steps?
- ADECOS Phase II: $DeSO_x$ tests at an existing distillation column with flue gas from the 50 kW_{th} unit

1000 MW_{el} oxyfuel plant study

TECHNISCHE UNIVERSITÄT DRESDEN

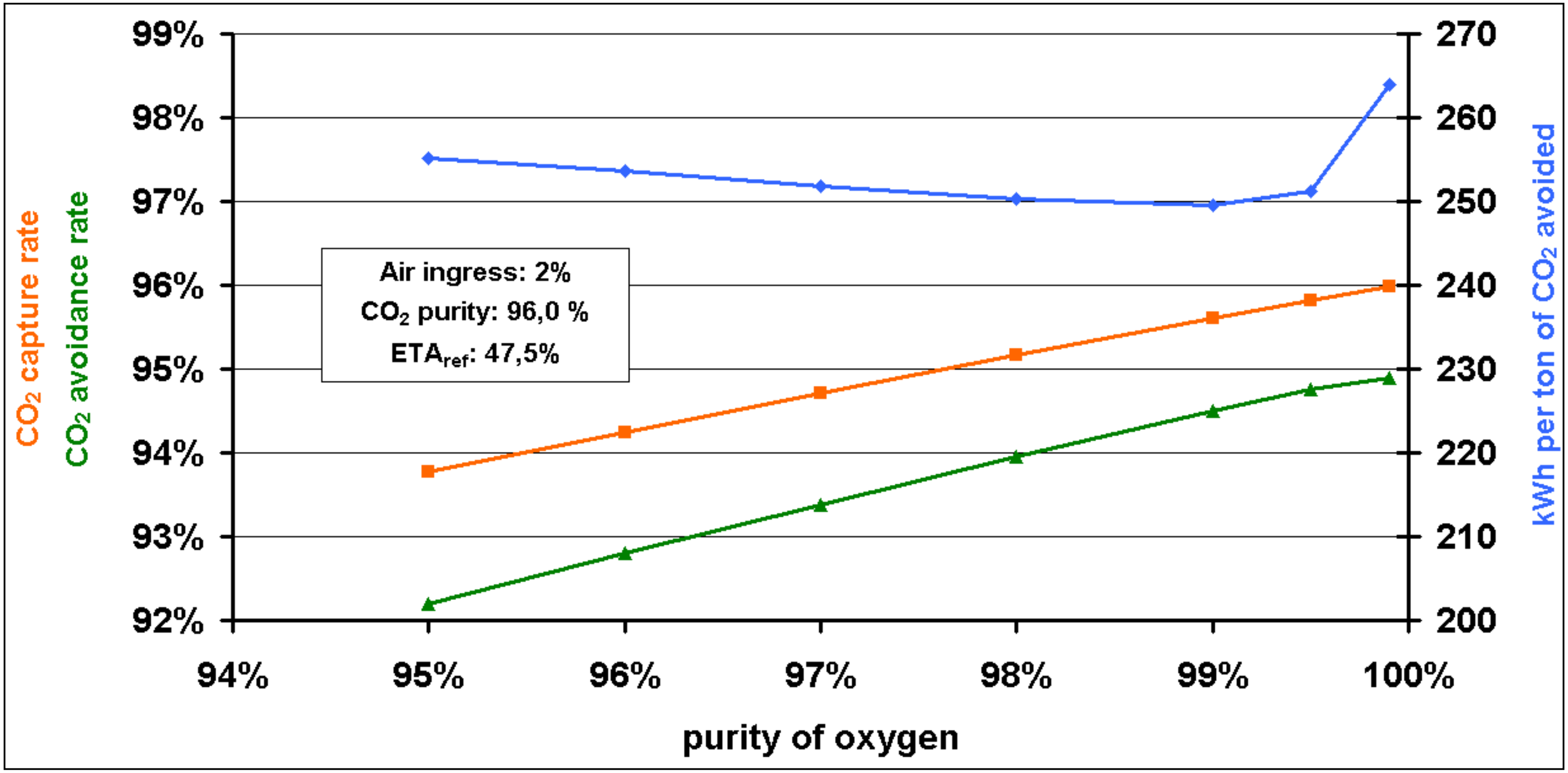




- Problem of efficient integration of additional oxyfuel plant components
- High own consumption

➔ **Best available technology to meet state-of-the-art efficiencies**

Process optimisation



- **Combining a variation of oxygen purity and an evaluation of the inerts removal process leads to an optimised ASU setup**

TECHNISCHE UNIVERSITÄT DRESDEN

Summary and Outlook

- TU Dresden very active in developing lignite-fired oxyfuel technology
- Experience with conventional coal-fired power plants coupled with innovative approaches
- Target: improving the efficiency of CO_2 separation from an Oxyfuel process

ADECOS Phase II: Intensify R&D activities

- Oxyfuel coal combustion fundamentals
- Optimisation of Oxyfuel power plant concepts and specific components (ASU, boiler, $DeSO_x$...)
- Evaluation and/or test of alternative and innovative process stages (e.g. $DeSO_x$ by distillation)

Thanks for your attention.

Questions?

contact:
Stefan Hellfritsch
stefan.hellfritsch@tu-dresden.de

Also have a look at our project website:
www.adecos.de

Overview of Research Activites on Oxy-Combustion at TU-München

Dipl.-Ing. Valentin Becher
Institut of Energy Systems

Developments in Oxy-Combustion Technology for Power Plants with CCS
A Young Researchers Forum

Hamburg 08.12.06

Outline

1. EU-Project FRIENDLY COAL
2. Concept of Controlled Staging
3. Proof of Controlled Staging concept
4. Conclusions

1. EU-Project FRIENDLY COAL

EU-Project FRIENDLY COAL

Advanced boiler concepts for CO_2-free hard coal fired power plants with oxyfuel technology

Coordinator:
- TU München

Partner:
- Siemens
- ENEL
- TU Graz
- TU Denmark

Friendly Coal
www.friendly-coal.eu

Research Fund for Coal & Steel

Work supported by the Research Fund for Coal and Steel under Contract-Nr: RFCR-CT-2006-00007

Project structure

Design of and experiments with 3 MW_{th} high recirculation-burner for oxycoal *(ENEL, TU Graz)*

Fundamental Research about Oxyfuel combustion of hard coals *(TU Denmark)*

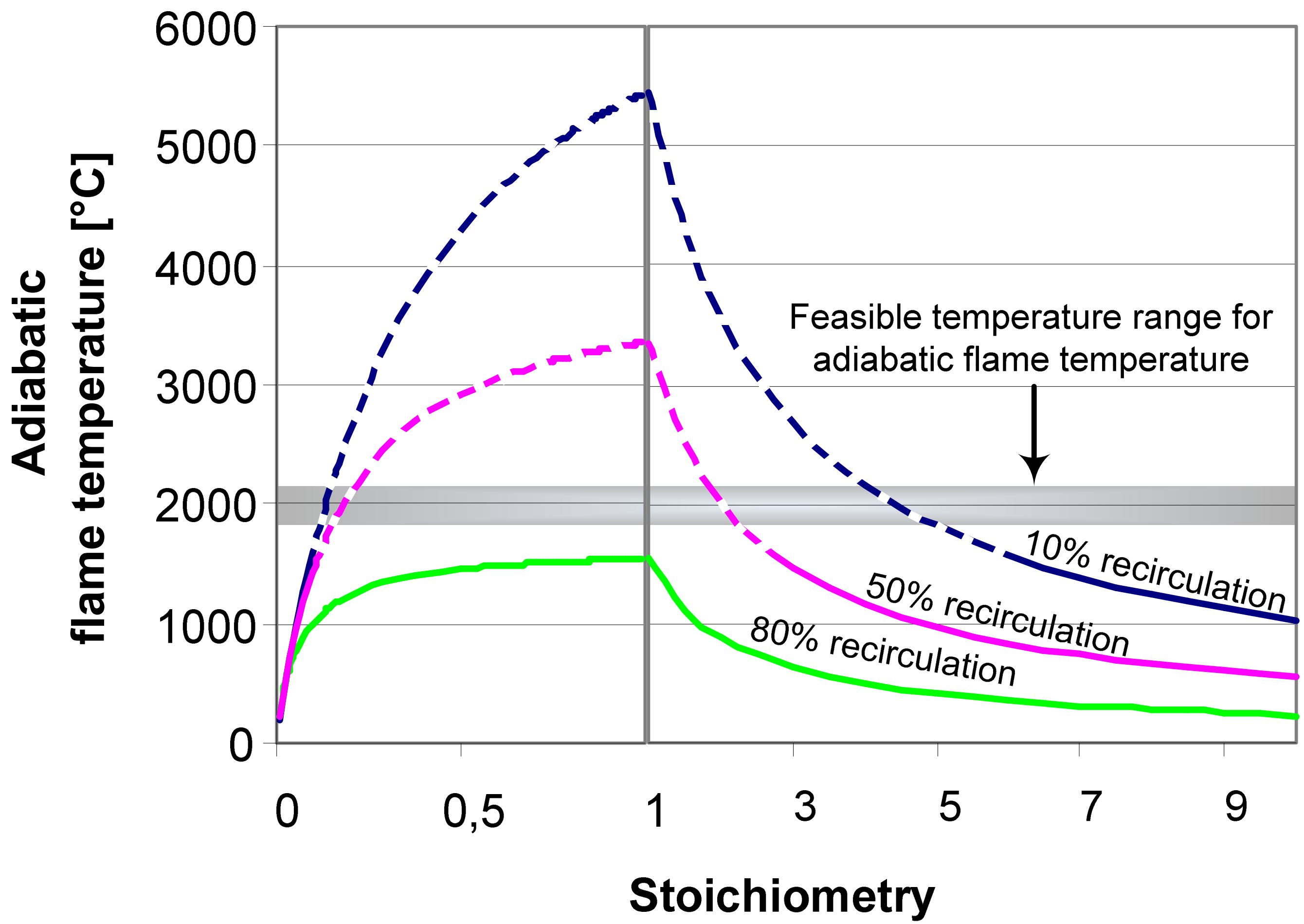
Experimental / CFD validation of Controlled Staging at 300 kW_{th} gas combustion facility *(TU München)*

Design und economics of 300 MW_{th} power plant *(Siemens, TU München, TU Graz)*

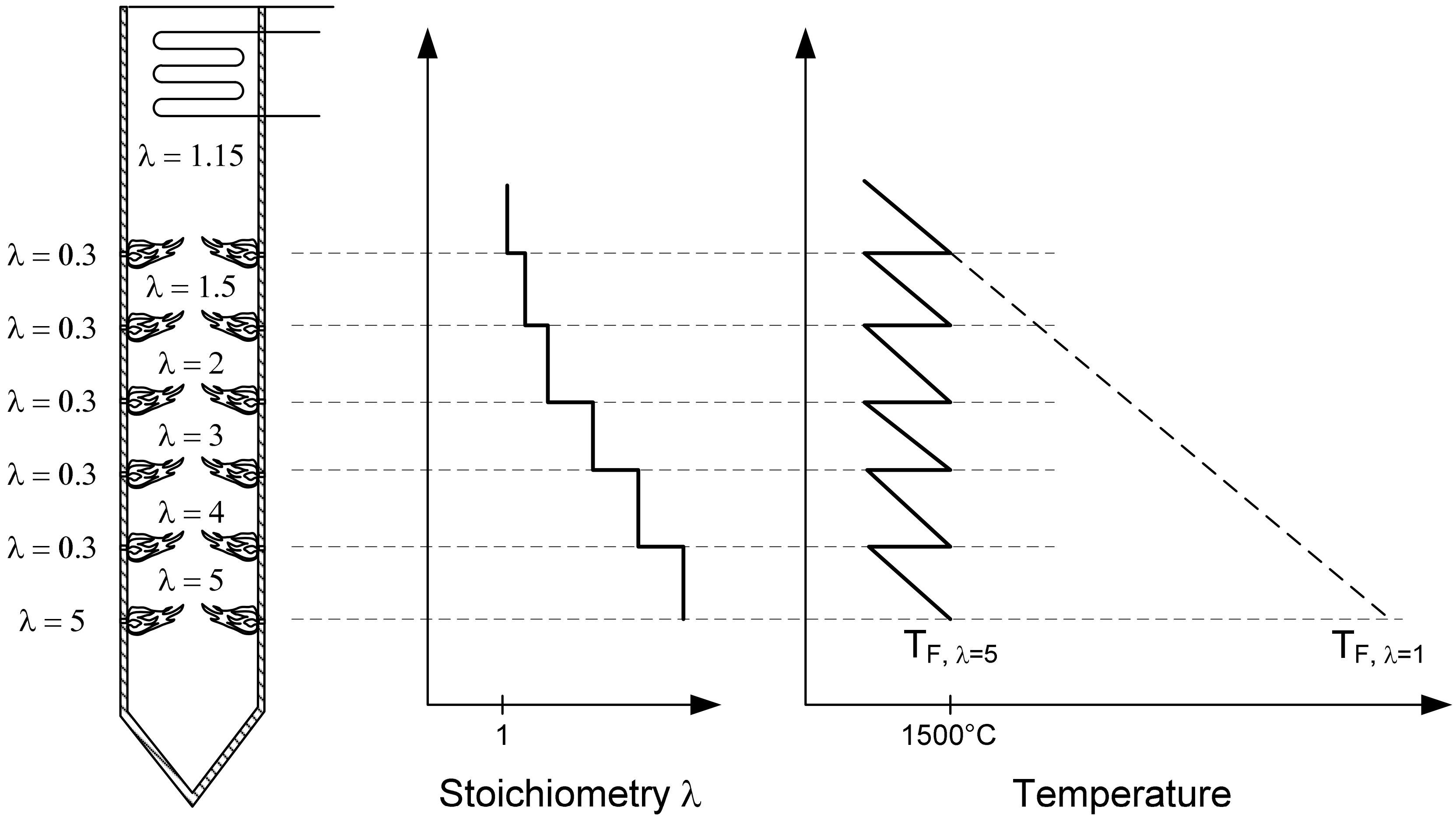
Friendly Coal
www.friendly-coal.eu

2. Concept of Controlled Staging

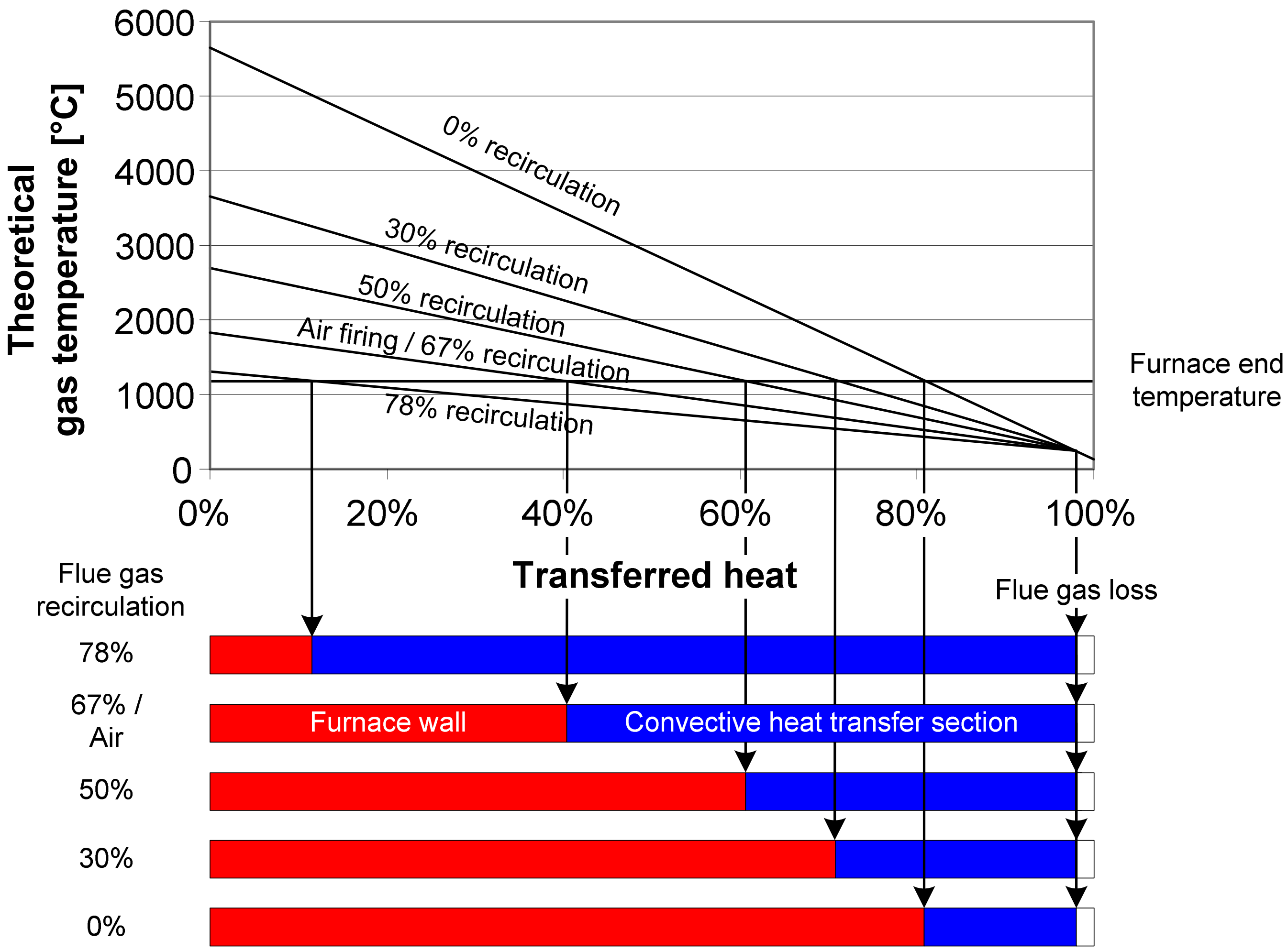
Adiabatic flame temperature



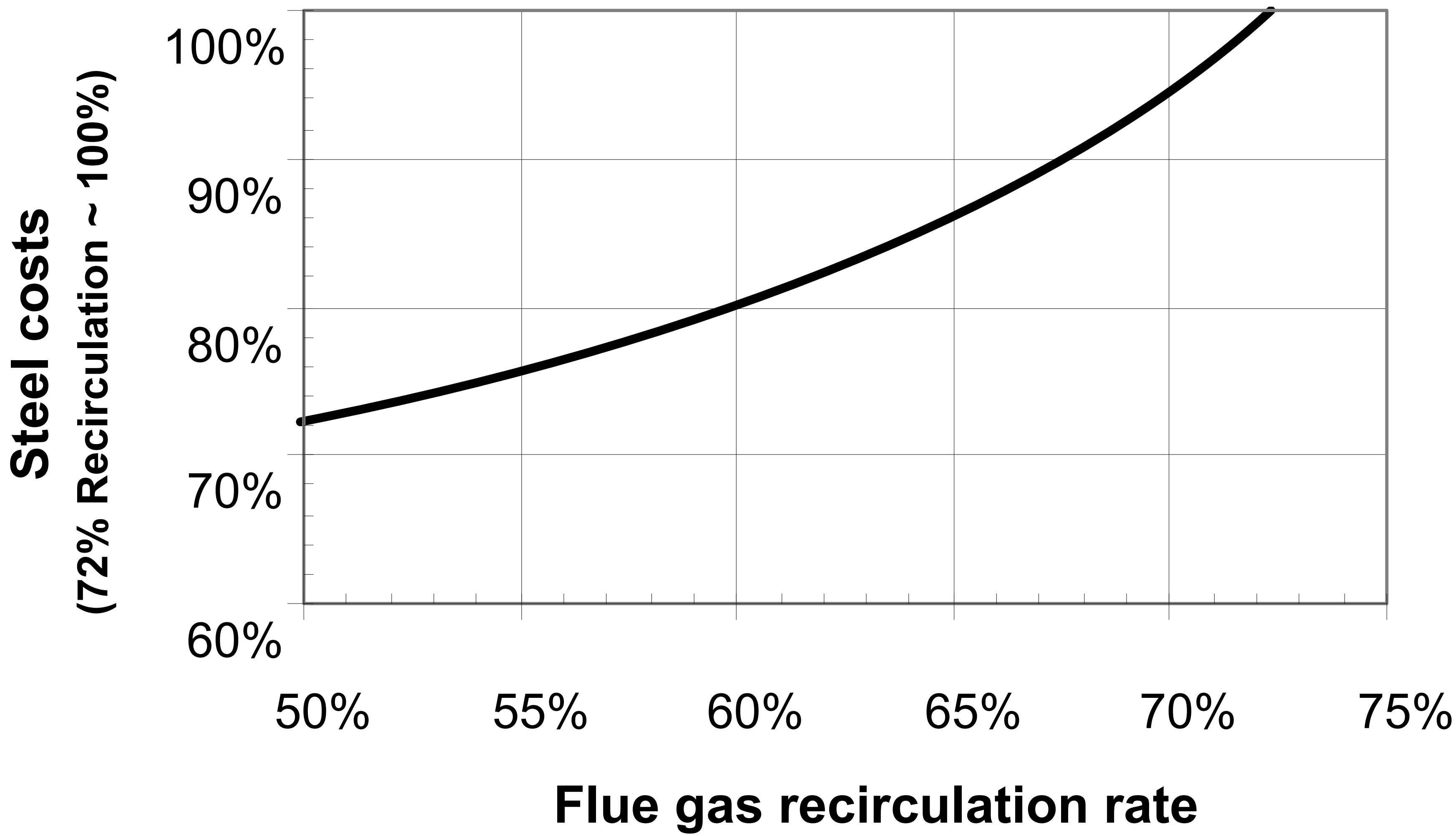
Controlled Staging with non-stochiometric burners



Transferred heat



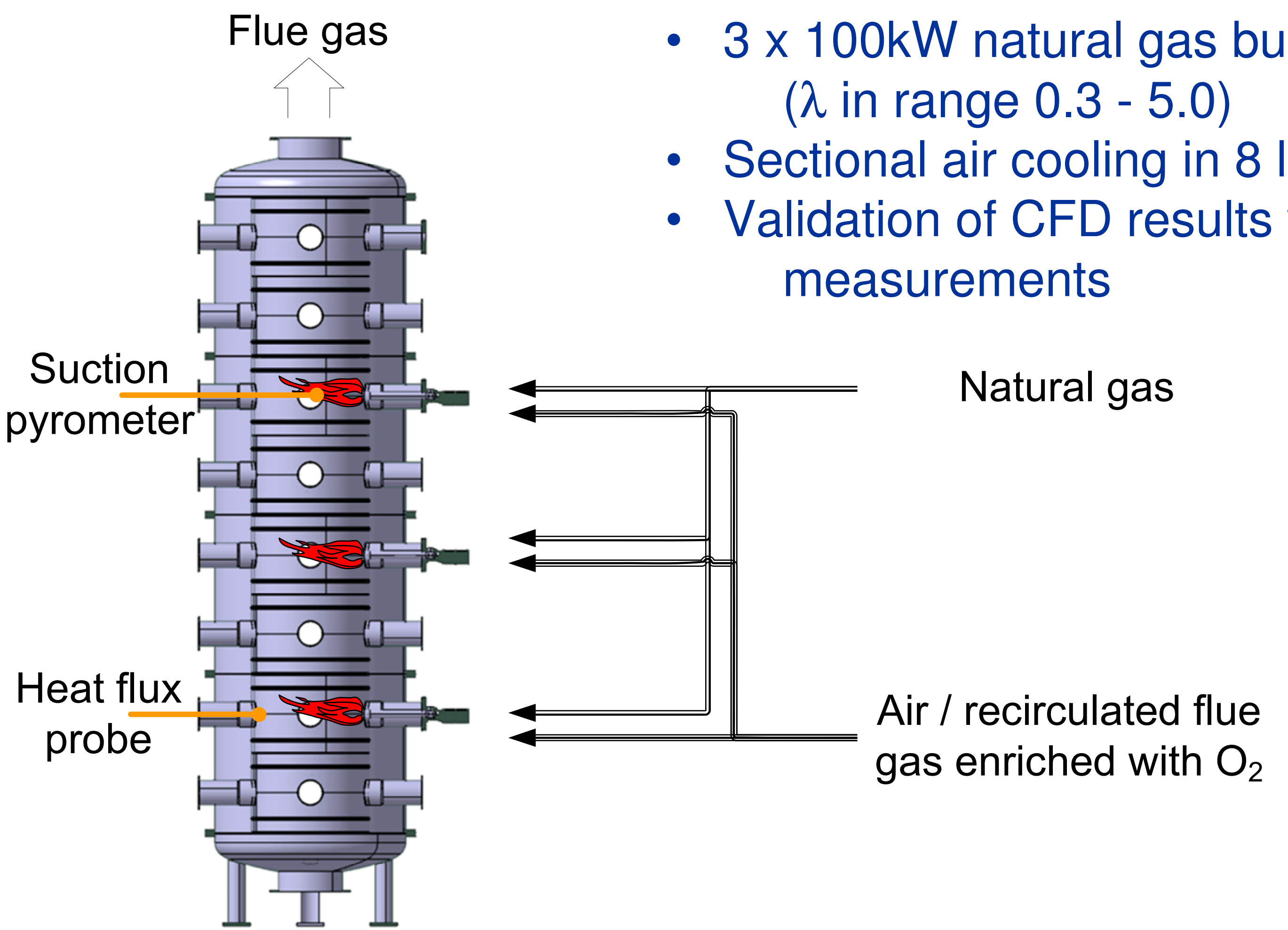
Boiler investment costs



3. Proof of Controlled Staging concept

Experimental setup

- 3 x 100kW natural gas burners (λ in range 0.3 - 5.0)
- Sectional air cooling in 8 levels
- Validation of CFD results with measurements



4. Conclusions

Conclusions

- *FRIENDLY COAL:*
  - *3 MW_{th}-burner with high recirculation rate*
  - *Controlled Staging with non-stochiometric burners*
- *Concept of Controlled Staging*
- *Reduction of boiler investment costs of 30%*
- *Experimental setup*

Friendly Coal
www.friendly-coal.eu

Thank you for your attention!

Friendly Coal

www.friendly-coal.eu