3rd MEETING OF THE OXY-COMBUSTION NETWORK

Report Number: 2008/5

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INTERNATIONAL ENERGY AGENCY

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ACKNOWLEDGEMENTS AND CITATIONS

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

The international research network on Oxy-Combustion is organised by IEA Greenhouse Gas R&D Programme in co-operation with IHI, JPower and JCoal.

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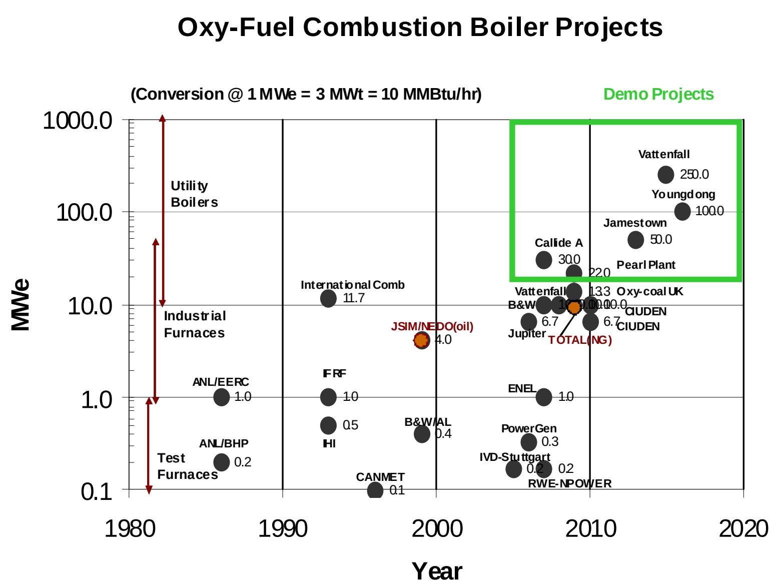
3^{rd} IEA GHG INTERNATIONAL OXY-FUEL COMBUSTION RESEARCH NETWORK

Yokohama, Japan5th and 6th March 2008

EXECUTIVE SUMMARY

The IEA Greenhouse Gas R&D Programme (IEA GHG) has been active in providing a forum for key industry players and stakeholders in the development of oxy-fuel combustion for power generation with CO_2 capture to present and discuss progress made. An international research network on oxy-fuel combustion was launched by IEA GHG in November 2005. At that time, there only 2 major large scale projects had been announced worldwide (Vattenfall's Schwarze Pumpe Project and CS Energy Callide Power Plant Retrofit Project). However at the 3rd network workshop held at Yokohama, Japan on the 5th and 6th of March 2008 presentations were given on 12 major large scale (i.e. >15MW$_{th}$) oxy-fuel combustion projects. These projects cover both large scale burner tests and feasibility studies for oxy-fuel combustion demonstration power plant,ranging from 50MWe to 250MWe. The number of projects now being discussed indicates the rapid development of oxy-fuel combustion as a capture technology option.

The development and the current status of oxy-fuel combustion technology are summarized in the figure below.



Updates on the various large scale oxy-fuel demonstration projects were presented during the meeting. Most of the large scale pilot plant projects, which also include the CO_2 storage, will be commissioned in mid-2008 to 2010. These include notable projects such as the Vattenfall Schwarze Pumpe project, the TOTAL Lacq Project and the CS Energy Callide-A Project. Several of the large scale burner tests will be operational between now and 2009. This includes the B&W 30MW$_{th}$ (currently operational), the Jupiter Oxygen 15MW$_{th}$ (testing to start this year), the Doosan Babcock 40MW$_{th}$ (testing to start in 2009) and the CIUDEN test facility to be commissioned in 2010.

During the 3rd network workshop several major developments were reviewed and new results are presented. These new developments included:

- In the area of development in oxy-fuel combustion burners and boilers (including emissions) it has been demonstrated that SO_3 emissions will be significantly higher compared to air firing. Increases in H_2S formation in the furnace are a possible impact of SO_2 accumulation due to flue gas recycle, however evidence of increased sulphur capture in the ash may be coal specific. Lower ash carbon contents have been observed with oxy-fuel combustion. Whilst, new SEM measurement data indicates that with oxy–fuel combustion larger particle sizes are formed during char burnout and ash formation.

- Development activities in oxy-CFB have gathered pace. This is primarily driven by two of the major large scale projects recently announced the CIUDEN Project in Europe and the Jamestown Project in the USA.

- Industrial gas companies (notably Air Liquide and Air Products) have confirmed that they are now offering improvements in the specific energy consumption of oxygen production from their cryogenic Air Separation Units (reduced from 200-220 kWh/tonne O_2 to 150-170 kWh/tonne O_2 by 2009–2010).

- New experimental results have been presented on the phase equilibria involving binary mixtures of CO_2 with various impurities.These results will aid in the validation of the coefficients used in the different equations of state (i.e. Peng Robinsons EOS). Further unresolved issues on this topic have been identified (for example the coefficients suggested for N_2O_4 and CO_2 mixture presented in 1901 literature should be further verified). On-going work/studies will be implemented within this year has been noted.

Additional issues and questions were raised over the course of the workshop included:

- CO_2 purity, which is a key design parameter of oxy-fuel combustion. The London and OSPAR Conventions have specified that the CO_2 streams allowed for storage under the seabed should be "Overwhelmingly CO_2". However this was considered too vague by the workshop participants. The Japanese Government has adopted a 99% purity specification in its marine law. Other regulatory developments in Europe, Australia and the USA have not yet set specific purity requirements. The discussion during the workshop highlighted the importance of clarifying and narrowing down the wide ranging specificationof the CO_2 purity quoted in various the literature.

- It has been highlighted that there is a lack of information on Hg emissions from oxy-coal combustion has been highlighted. Potential operation impact of mercury on the CO_2 processing unit has been noted.

In addition, there is a general question on what and how much new information from the large scale demonstration projects will be publicly shared has been raised. Most of the major stakeholders within the oxy-fuel combustion community have agreed that it is important information should be shared both ways in order to validate and to prevent any duplication of work. However, unrestrained knowledge sharing is still under discussion because of commercial interest and proprietary knowledge issues.

3rd IEA GHG INTERNATIONAL OXY-FUEL COMBUSTION RESEARCH NETWORK

Yokohama Conference Centre
Yokohama, Japan

5th – 6th March 2008

1. INTRODUCTION

The IEA Greenhouse Gas R&D Programme (IEA GHG) has developed an international research network on oxy-fuel combustion to provide a forum to various key industry players and stakeholders to discuss developments in oxy-fuel combustion for power generation with CO_2 capture.

This report covers the third workshop in the series which was held at the Yokohama Conference Centre, Yokohama, Japan on the 5th and 6th of March 2008. The workshop was was hosted by IHI, JCoal, and JPower.

During the inaugural workshop held in Cottbus, Germany, there were only 2 major large scale projects announced worldwide (Vattenfall's Schwarze Pumpe Project and CS Energy Callide Power Plant Retrofit Project). This year, at the 3rd details of 12 major large scale (i.e. >15MW_{th}) oxy-fuel combustion projects covering large scale burner testing to feasibility studies on oxy-fuel combustion demonstration power plant (100MWe to 250MWe)) were discussed.

This report presents an overview of the workshop and summarises the current status of development of oxy-fuel combustion. 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-fuel combustion technology.

IEA GHG would like to acknowledge and thank Prof. Keiji Makino (IHI), Dr. Toshihiko Yamada (IHI), Dr. Takashi Kiga (JCoal), and Dr. Nobuhiro Misawa (JPower) and their colleagues for their support and assistance in organising the 3rd oxy-fuel combustion network workshop.

2. WORKSHOP OVERVIEW

In recognition of the different efforts by industry, academia and other research institutes to develop and demonstrate the techno-economic feasibility of oxy-fuel combustion technology as a CO_2 capture option for power plant application in the near future; the IEA GHG initiated the International Network for Oxy-Fuel Combustion.

The aim of this network is: to provide an international forum for organisations with interests in the development of oxy-fuel combustion technology to discuss issues relevant to the development of the technology.

The inaugural workshop of the network was hosted by Vattenfall AB in Cottbus, Germany on the 29th and 30th of November 2005. The workshop was accompanied by 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.. The 2nd meeting of Oxy-Combustion Research Network was held in Windsor, CT, USA and was hosted by Alstom.

To follow up the discussions from the earlier workshops, 3rd workshop was organised this time in Japan. The 3rd workshop started with a facility visit to Central Research Institute of Electric Power Industry (CRIEPI) on the 4th of March 2008 anmd with a visit to several research facilities which includes the combustion research facility, biomass syngas production facility, fuel cell technology and gasification unit.

Figure 1: Group photograph taken during the CRIEPI facility visit.

The opening session started with two keynote presentations by Dr. Makoto Akai of AIST and Prof. Ken Okazaki of Tokyo Institute of Technology. The second day started with a keynote presentation by Dr. Marie Anheden of Vattenfall Research R&D AB.

The two day meeting consists of 38 other presentations which presented a wide range of topics looking at; experimental results, on-going studies, new developments and included discussion on various issues regarding oxy-fuel combustion technology for power plant applications.
The first day of the meeting ended with a discussion forum led by Prof. Jost Wendt (Utah University covering the various key issues related to regulatory requirements, permitting issues and CO_2 quality. The 2nd day concluded with a panel discussion providing an opportunity for major large scale pilot/demonstration projects to present any updates to their projects.

The agenda of the workshop is presented in Table 1.

Table 1: Agenda of the Workshop

5th March 2008 – AGENDA (Day 01)		
Presentation 01	Welcome Remarks / Brief Introduction, T. Namiki (JCoal),	
Presentation 02	Welcome Response / Administrative Announcement, J. Topper (IEA Greenhouse Gas R&D Programme)	
SESSION 1: Challenges of CCS and Oxy-Combustion - Keynote Address (Day 01) *Chairperson: John Topper, IEA Greenhouse Gas R&D Programme, UK*		
Keynote Presentation 01: CCS Policy and Overview in Japan – Dr. Makoto Akai, AIST, Japan		
Keynote Presentation 02: Technical Consideration and Challenges of Oxy-Combustion – Prof. Ken Okazaki, TIT, Japan		
	Session 2a: Oxy-Combustion Fundamentals *Chair: Klas Andersson, Chalmers University, Sweden*	***Session 2b: On-going Experimental Studies*** *Chair: John Smart, RWE Npower, UK*
Presentations 03 & 07	Performance of PF Boilers Retrofitted with Oxy-Coal Combustion: Understanding Coal Burnout, Coal Reactivity, Burner Operation, and Furnace Heat Transfer T. Wall - Newcastle University, Australia	E.On UK's Pilot Scale Oxy-Fuel Combustion Experience: Development, Testing and Modelling B. Goh - E.On UK
Presentations 04 & 08	Evaluation of Gas Radiation Modelling in Oxy-Fired Furnaces R. Johansson - Chalmers University, Sweden	Fundamental Studies and Pilot Scale Evaluation of Oxy-Coal Firing in Circulating Fluidized Bed Boilers E. Eddings -University of Utah, USA
Presentations 05 & 09	Stabilising Swirl Pulverized Coal Flames Under Oxy-fuel Conditions D. Toporov - RWTH Aachen University, Germany	Impact of Combustion Conditions on Emission Formation (SO_2, NO) and Fly Ash Composition J. Maier – IVD University of Stuttgart
Presentations 06 & 10	Model Validation Studies for Pulverised Coal Jet Ignition in O2/CO2 Environment J. Wendt - University of Utah, USA	Technical Consideration of Mercury Emissions in an Oxy-Coal Power Plant with CO_2 Capture S. Santos – IEA Greenhouse Gas R&D Programme, UK
	Session 2c: Oxy-Combustion Systems Studies *Chair: Kevin McCauley, B&W, USA*	***Session 2d: On-Going Experimental Studies*** *Chair: Takashi Kiga, JCoal, Japan*
Presentations 11 & 15	Efficiency Increase of the Oxyfuel Process by Waste Heat Recovery Considering the Effects of Flue Gas Treatment M. Klostermann - TUHH, Germany	Understanding Potential Environmental Impacts of Oxy-Fuel Combustion C. W. Lee and A. Miller - US EPA
Presentations 12 & 16	Consideration for Oxy-Fuel Coal Fired Combustion Power Plant System Integration H. Hack - Foster Wheeler	High Temperature Reduction of Nitrogen Oxides in Oxy-Fuel Combustion F. Normann, Chalmers University, Sweden
Presentations 13 & 17	3rd Generation Oxy-Combustion Systems C. Salvador - CANMET, Canada	Understanding the Effects of O_2 and CO_2 on NOx Formation During Oxy-Coal Combustion C. R. Shaddix - Sandia Laboratory
Presentations 14 & 18	Oxy-Combustion: Research, Development and Systems Analysis T. Fout - DOE/NETL, USA	Evaluation of CO_2 Capturing – Repowering System Based on Oxy-Fuel Combustion for Utilising Low Pressure Steam P. S. Pak Osaka University, Japan
Session 3: Oxygen Production and CO_2 Processing *Chairperson: Minish Shah, Praxair, USA*		
Presentation 19	Phase Equillibria Measurements and their Application for the CO_2 Separation from CO_2 Rich Gases R. Eggers, and D. Köpke, TUHH, Germany	
Presentation 20	Purification of Oxy-Fuel Derived CO_2 V. White, Air Products, UK	
Presentation 21	Update on Advanced Developments for ASU and CO_2 Purification Units for Oxy-Combustion J.P. Tranier, N. Perrin, A. Darde, Air Liquide, France	
Presentation 22	Consideration for Removal of Impurities from CO_2 Rich Flue Gas of Oxy-Fuel Combustion M. Anheden, Vattenfall, Sweden	
Presentation 23	Technical Consideration for a Very Large Scale Air Separation Unit for Large Scale Coal Fired Power Plant Application K. Fogash, Air Products, UK	

Session 4: Discussion Forum: Quality of CO_2 for Storage – What are the Issues and Opportunities… *Chairperson: Prof. Jost Wendt, University of Utah, USA*	
Presentations 24 & 25	Andy Miller, US Environmental Protection Agency, USA Vince White, Air Products, UK

6th March 2008 – AGENDA (Day 02)	
Session 5: Future of Oxy-Coal Combustion – Keynote Address (Day 02) *Chairperson: Prof. Keiji Makino, IHI, Japan*	
Keynote Presentation 03, Vattenfall Schwarze Pumpe Pilot Plant _ Dr Maries Anheden, Vattenfall R&D AB, Sweden	
Presentation 26	APP Project: Overview of Oxy-Fuel Working Group – A Platform for Cooperation Prof. Terry Wall, University of Newcastle, Australia
Presentation 27	Oxy-Combustion Activities at Tsinghua University: CO_2 Capture Based on Chemical Looping Cycles Prof. Ningsheng Cai, Tsinghua University, China
Presentation 28	Capture Ready Plant Concept: Retrofitting Power Plant with Oxy-Combustion John Davison, IEA Greenhouse Gas R&D Programme, UK
Session 6: Large Scale Burner and Boiler Development – Technology and Equipment Manufacturer Perspective *Chairperson: Chris Spero, CS Energy, Australia*	
Presentation 29	Recent Test Results on Oxy-Fuel Combustion Using the Pilot-Scale Test Facilities T. Uchida, T. Yamada, K. Hashimoto, S. Watanabe; IHI, Japan
Presentation 30	Scale Up of Oxy-Coal Combustion at B&W's 30MWth CEDF H.Farzan, K.J. McCauley, Babcock & Wilcox, USA; R.Varagani, Air Liquide, USA
Presentation 31	Alstom Development of Oxy-Fired PC and CFB Power Plants J. Marion, Alstom Power, USA
Presentation 32	Oxy-Combustion UK Project Update: Development of 40MWth Burner Testing Programme D. Fitzgerald, Doosan Babcock, UK
Presentation 33	Jupiter Oxygen - 15MWth Oxy-Combustion Boiler Test Results B. Patrick, Jupiter Oxygen, USA
Session 7: Large Scale Demonstration and Pilot Scale Projects *Chairperson: Sho Kobayashi, Praxair, USA*	
Presentation 34	Callide Oxyfuel Project – Technical evaluation of the oxy-combustion and CO_2 capture system design C. Spero, T. Yamada, E. Sturm, and D. McGregor CS Energy, Australia; IHI, Japan; Air Liquide, France and GLP, Australia
Presentation 35	The CO_2 Pilot at Lacq: An Integrated Oxy-Combustion CO_2 Capture and Geological Storage Project N. Aimard, and C. Prebende TOTAL, France
Presentation 36	Test Facilities for Advanced Technologies for CO_2 Abatement and Capture in Coal Power Generation V. Cortes CIUDEN, Fundacion Estata Ciudad de la Energia, Spain
Presentation 37	Oxy-Combustion Research Activities in S. Korea – Overview to the Youngdong 100MWe Oxy-Combustion Power Station Project Development J. S. Kim, S. M. Choi, Y. J. Kim and S. C. Kim* KIST, KAIST, KEPRI, Korea
Presentation 38	Oxy-Coal Combustion Demonstration Project M. Shah, D. Bonaquist, R. Victor, M. Shah, H. Hack, A. Hotta, D. Leathers Praxair, USA; Foster Wheeler, USA/Finland; and Jamestown Board of Public Utilities

3. ATTENDANCE

The workshop brought together 103 participants from industry, research institutes and universities covering 18 countries worldwide. The delegate list is given in Annex I. The number of participants attending the workshop has grown significantly over the three years.

4. AGENDA – Presentations by Attendees

The agenda of the meeting is presented in Table 1 . Copies of slides appear in the same order in Annex II.

5. CURRENT STATE OF UNDERSTANDING – PRESENTATION HIGHLIGHTS

What were the new developments in oxy-fuel combustion presented during the workshop?

a) Regulatory and permitting issues were raised as an important issue during the workshop. The presentation by Dr. Akai [Keynote Presentation 01] presented the Japanese approach and interpretation of the International Maritime Organisations conventions for CO_2 storage under the sea bed. However, several participants considered the adoption of 99% purity for CO_2 as an unnecessary economic penalty for oxy-fuel combustion. The workshop [see presentations 22, 25, and 31] highlighted the importance and need to clarify and narrow down the range values for CO_2 purity suggested in various public domain literatures on oxy-fuel combustion. Whilst it is noted that CO_2 streams from oxy-fuel combustion could be technically processed to achieve a high purity, this would come at a cost.

b) Prof. Okazaki [Keynote Presentation 02] highlighted the importance of developing various sub-models that can be used in CFD to simulate the combustion process of the oxy-PC and oxy-CFB. This includes development of:
   - heat transfer sub-model for the radiant and convective sections of the boiler,
   - coal jet ignition sub-model,
   - char burnout and devolatilisation sub-model,
   - ash partitioning sub-model which also to include modelling of ash deposition and speciation of the trace metal,
   - combustion by-product sub-model which also to include the modelling of specific pollutant (i.e. NOx and SOx) emissions and trace metal emissions in the flue gas.
   - integrated furnace sub-mode.

   Development of these sub-models requires further work on the fundamental understanding of the combustion chemistry, aerodynamics, and pollutant formation/reduction mechanisms.

c) The industrial gas companies present (namely Air Liquide and Air Products) confirmed that they are now offering improvements in the specific energy consumption of oxygen production from the cryogenic Air Separation Unit's - reduced from 200-220 kWh/tonne O_2 three years ago to 150-170 kWh/tonne O_2 (by 2009–2010). [Presentation 21 & 23]

d) Development activities in oxy-CFB have gathered pace. This is primarily driven by two of the major large scale projects announced one in Europe (CIUEDEN Project) and one in the USA (Jamestown Project). [Presentations: 08, 12, 31, 36, 38]

e) New experimental results have been presented on phase equilibria between impurities and CO_2 looking at validation of experimental data and empirical models for coefficient characterising the properties of the gas mixtures (ternary and binary mixtures). Further unresolved issues on this topic have been identified with on-going work/studies to be implemented within this year. [Presentations: 19, 21].

New experimental results were presented that aid the further understanding of the oxy-fuel combustion process. Some of these important results are enumerated below:

a) In the area of heat transfer modelling:

The presentation by Mr. Johansson [Presentation 04] has indicated that the flame intensity measurement is significantly higher that the results obtained from Weighted Sum of Gray Gases (WSGG) Model. This further stressed that the existing parameters of the WSGG model are intended for air fired conditions and often yield significant errors for conditions relevant for oxy-fired furnaces.

It was also noted that the latest WSGG parameters give results within 20% of the reference model (based on narrow band model). These parameters could be acceptable in terms of computational cost and accuracy.

b) In the area of coal jet ignition:

Work done by IHI and NSW University [Presentation 03] indicated that there are significant ignition delays during partial load firing with oxy-fuel combustion. This has been attributed to the difference between the furnace temperature and the momentum flux as observed during the combustion trials done at the IHI test facility in Aiolo, Japan.

c) In the area of char burn out modelling:

The presentation by Prof. Wall [Presentation 03] indicated that char morphology is significantly larger in oxy-fuel combustion mode than in air fired mode.

The amount of carbon in ash (an indication of combustibility of the char) could be significantly lower during oxy-fuel combustion than during air-firing. However, current results indicated that this observation could be coal specific and could also be affected by the manner on how the flue gas is recycled [Presentations 03 & 07].

This observation has been indirectly corroborated from the new results obtained by IVD Stuttgart indicating an increase in the level of carbonization and sulphation from the ash deposit collected in various combustion tests [Presentation 09].

d) In the area of Pollutant formation and reduction mechanisms:

An increase in SO_3 emissions during oxy-fuel firing using the Lausitz Lignite were observed during tests at IVD Stuttgart done last year. These results confirm the results obtained from the early studies done by ANL during the 1980s indicating increased emissions by about 4-5 times as compared to air fired case. Further investigations should be pursued since this observation could be very coal specific. [Presentation 09 & 10].

The results presented by Dr. Maier [Presentation 09] with regard to the sulphation of the ash clearly supported the mechanisms suggested by Prof. Okazaki [Keynote Presentation 01] suggesting that oxy-fuel combustion promotes sulphur absorption by calcium based solids (i.e. $CaCO_3$ or CaO) at high temperature conditions due to high level recirculation of SO_2 and also inhibit the decomposition $CaSO_4$. The keynote presentation by Prof. Okazaki [Keynote Presentation 02] explained in detail the mechanism involved.

e) In the area of ash deposition, fouling and slag formation:

Recent results presented by Dr. Goh [Presentation 07] indicated that a normally non-slagging coal when burned during air fired conditions could turn out to be slagging when burned under oxy-fuel combustion conditions. Currently there is no clear explanation to why this has occurred. Nonetheless, they have attributed this observation to the tendency of higher deposition rate and longer residence time during oxy-fuel combustion in which this theory should be validated further.

6. KEY ISSUES

What are the key issues and on-going work identified during the workshop?

a. During the discussion forum, Dr. Miller [Presentation 25] raised the following fundamental questions which would impact the deployment of oxy-fuel combustion technology for power generation with CO_2 capture.
   - Who owns the CO_2?
   - What are the subsurface resource rights and laws?
   - Who has the liability for leaks into the air or groundwater, long-term monitoring, and accidents?
   - How are trans-boundary reservoirs handled?
   - Is CO_2 a waste or a commodity? Does CO_2 purity change the classification of the CO_2 product stream?

b. These questions all need to be addressed in a comprehensive way with respect to CO_2 capture and storage. It is noted that these issues are being discussed in different forums both regionally and internationally, IEA GHG is actively involved in many of these forums.

c. CO_2 purity is a key design parameter of oxy-fuel combustion. The international agreement based on London and OSPAR Conventions has ruled that the CO_2 streams allowed for storage under the seabed should be “Overwhelmingly CO_2” . However this was considered to be too vague. This has been adapted in recent Japanese government policy where a 99% purity limit was set for CO_2 that would be injected into sub sea bed geological structures. No other regulatory development in Europe, Australia or North America had yet set a limit for CO_2 purity. The discussion during the workshop has highlighted the importance of clarifying and narrowing down the wide ranging specification on the CO_2 quality quoted in the literature.

d. The following important aspects have been identified as an area where collaboration among major stakeholders should be undertaken. These includes
   - Permitting and long term liability issue in capture of CO_2 and its storage.
   - Health and Safety (especially in the safety handling of CO_2 / O_2 mixture).
   - Education and training

e. The presentation by Dr. Tranier [Presentation 21] highlighted the importance of knowing as much as possible about the phase equilibria between mixtures of impurities and CO_2. One of the key mixtures missed out from the phase equilibrium work done by TUHH [Presentation 20] was the CO_2-NO_2/N_2O_4, because this was assumed to be of negligible importance. However, it was stressed by Dr. Tranier that this mixture should be further investigated since data obtained during the early 1900's are not sufficiently reliable enough to be used for the current work.

f. The lack of current information on Hg emissions from oxy-coal combustion has been highlighted. The potential adverse operation impact of mercury on the CO_2 processing unit has been noted. [Presentation 10].

g. A key area of development in oxy-fuel combustion technology is the development of flue gas clean-up equipment for removal of impurities such as Cl and SO_3 prior to the flue gas being introduced to the CO_2 processing unit. Some indicative activities on these aspects have been presented during the meeting [Presentation 29, 30, 32].

7. SUMMARY

During the 1st oxy-fuel combustion workshop, several different issues involving the development of oxy-fuel burner and boilers, as well as development in the Air Separation Unit and CO_2 processing unit were identified. During the 2nd and 3rd workshops several of these issues were dis**c**ussed in more detail. In a positive note, several new results have been presented sin this meeting therefore indicating good progress has been made in the past three years. A
During this workshop, 12 major large scale projects were presented and updated. A list of these projects is given in Table 2. The development and the current status of oxy-fuel combustion technology are summarized in the Figure 2.

Most of the stakeholders involved in these projects agreed that demonstration of the technology is the next step in the development of oxy-fuel combustion application for power generation applications. Depending on the success of the various pilot plant projects, it could be inferred that by 2015, at least one demonstration project of > 250MWe would be deployed. In parallel to the development of high efficiency pulverised coal fired boilers (i.e. development of 700^oC and 300 bar steam parameter), it should be expected that the integration of such technology to the oxy-fuel fired boiler would be the next step in the development of this technology in the next decade to come.

During the discussion forum, one of the key issues identified is the requirement for clarity in the regulatory and permitting procedures. This also includes clarity on the appropriate rules for CO_2 purity.

Finally, one of the important messages during the meeting was conveyed by Prof. Makino, who stressed the importance of collaboration. He likened the oxy-fuel combustion community to several ships connected to each other. He noted that each of these ships represents a major in oxy-fuel combustion development in the next couple of years. He further noted that if one of the ships sinks then this could cause all of the other ships to sink with it.

An important point for future considerations, which have implications for future network meetings, is the question on what and how much new information from large scale demonstration projects would be publicly shared? Most of the major stakeholders within the oxy-fuel combustion community have agreed that it is important information should be shared both ways in order to validate and to prevent any duplication of work. However, unrestrained knowledge sharing is still under discussion because of commercial interest and proprietary knowledge issues.

Table 2: Major oxy-fuel combustion projects underway or planned for power generation applications

PROJECT	**Location**	**MWt**	**Start up**	**Boiler Type**	**Main Fuel**	**CO_2 Train**
B & W	USA	30	2007	Pilot PC	Bit, Sub B., Lig.	
Jupiter	USA	20	2007	Industr. No FGR	NG, Coal	
Oxy-coal UK	UK	40	2008	Pilot PC		
Vattenfall	Germany	30	2008	Pilot PC	Lignite (Bit.)	**With CCS**
Total, Lacq	France	30	2009	Industrial	Nat gas	**With CCS**
Pearl Plant	USA	66	2009	22 MWe PC	Bit	Side stream
Callide	Australia	90	2010	30 MWe PC	Bit.	**With CCS**
Ciuden - PC	Spain	20	2010	Pilot PC	Anthra.(Pet ck)	?
Ciuden - CFB	Spain	30	2010	Pilot CFB	Anthra.(Pet ck)	?
Jamestown	USA	150	2013	50 MWe CFB	Bit.	**With CCS**
Vattenfall Janschwalde	Germany	~1000	2015	~250 MWe?	Lignite (Bit.)	With CCS
Youngdong	Korea	~400	2016?	~100 MWe PC?	?	?

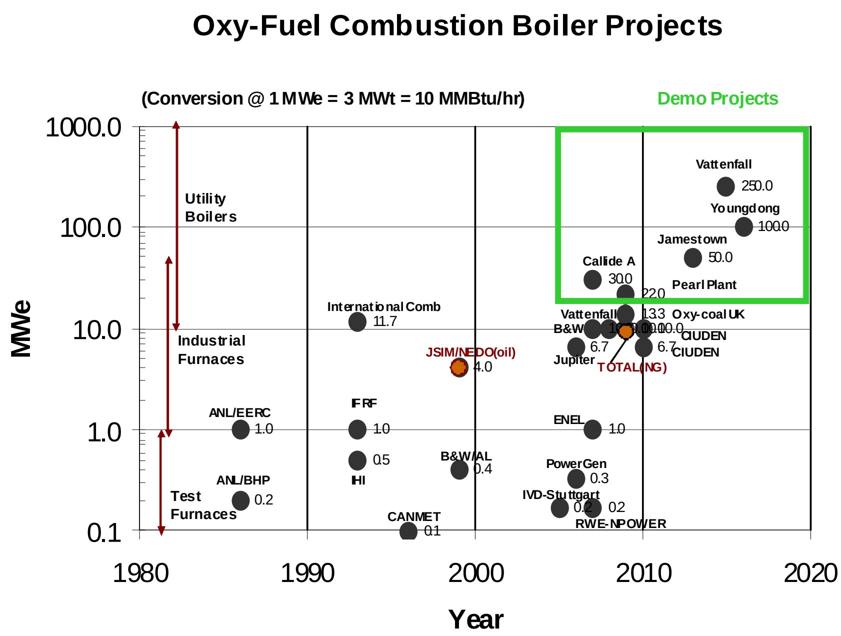


Figure 2: Development and Current Status of the Oxy-fuel Combustion Technology

3rd Oxy-Combustion Network Meeting, Yokohama, 5th-6th March 2008

Attendee List

Ali Hoteit	IFP	Hideki Gotou	J-POWER
Akemitsu Akimoto	JCOAL	Hiromichi Kameyama	Japan
Andreas Kempf	Imperial College London	Hisao Makino	CRIEPI
Antonio Diego-Marin	Instituto de Investigaciones Electricas	Hisashi Kobayashi	Praxair Inc.
Arto Hotta	Foster Wheeler Energia Oy	Hong-Shig Shim	Reaction Engineering International
Barry Waining	IEA	Honma Kazumichi	Mitsui
Ben Goh	E.On UK	Horst Hack	Foster Wheeler North America Corp.
Brian Patrick	Jupiter Oxygen Corp	Jean-Pierre Tranier	Air Liquide
Cai Ningsheng	Tsinghua University	Jianglong Yu	University of Newcastle
Charles McConnell	Praxair Inc.	Jim Craigen	ACARP / COAL21
Charles Miller	EPA Office of Research and Development	John Davison	IEA Greenhouse Gas R&D Programme
Chris Spero	CS Energy Ltd.	John Marion	Alstom Power Inc.
Christian Bergins	Hitachi Power Europe GmBH	John Smart	RWE Npower PLC
Christopher Shaddix	Sandia National Laboratories	John Topper	IEA Greenhouse Gas R&D Programme
Claude Prebende	TOTAL	John Wheeldon	EPRI
Daniel Koepke	Hamburg University of Technology	Jong Soo Kim	Korea Institute of Science and Technology
David Fitzgerald	Doosan Babcock Energy Ltd.	Jörg Maier	IVD-Stuttgart
Denis Cieutat	Air Liquide	José Miguel González Santaló	Instituto de Investigaciones Electricas
Dobrin Toporov	RWTH Aachen	Jost Wendt	University of Utah
Eric Eddings	University of Utah	Katsuyoshi Ando	JCOAL
Etienne Sturm	Air Liquide	Keiichiro Hashimoto	IHI
Euan Cameron	Doosan Babcock Energy Ltd.	Keiji Makino	IHI
Frank Kluger	Alston Power Systems GmbH	Ken Okazaki	TIT
Fredrik Normann	Chalmers University of Technology	Ken Yamamura	Mitsui
Gerald Kinger	EVN AG	Kentaro Nishida	J-POWER
Gerard Hesselmann	Doosan Babcock Energy Ltd.	Kevin Fogash	Air Products
Gyung-Min Choi	Pusan National University	Kevin McCauley	Babcock & Wilcox Company
Hamid Farzan	Babcock & Wilcox Company	Klas Andersson	Chalmers University of Technology
Kunjuraman Sivaramakrishnan	Bharat Heavy Electrical Ltd. (BHEL)	Kourosh Zanganeh	CANMET, Natural Resources Canada

Lars Strömberg	Vattenfall AB
Makoto Akai	AIST
Marie Anheden	Vattenfall R&D AB
Mario Ditaranto	SINTEF Energy Research
Martin Burböck	EVN AG
Masaharu Yamamoto	J-POWER
Masahiro Hosokawa	J-POWER
Mathias Klostermann	Hamburg University of Technology
Mikko Varonen	Metso Power
Minish Shah	Praxair Inc.
Nobuhiro Misawa	J-POWER
Ole Biede	Vattenfall A/S
Per Christer Lund	Royal Norwegian Embassy, Tokyo
Philippe Court	Air Liquide
Pyong Sik Pak	Osaka University
Ram Narula	Bechtel Power Corporation
Robert Johansson	Chalmers University of Technology
Sheishier Krishnamoorthy	Bharat Heavy Electrical Ltd. (BHEL)
Sangmin Choi	Korea Advanced Institute of Science and Technology
Satoshi Motohashi	Chiyoda
Seung-Mo Kim	Pusan National University
Shinichiro Omachi	Mitsui
Stanley Santos	IEA Greenhouse Gas R&D Programme
Stina Rydberg	Vattenfall Power Consultant
Sung Chui Kim	Korea Electric Power Research Institute
Susan Roces	De La Salle University
Syuzo Watanabe	IHI
Tadashi Itoh	Chiyoda
Takashi Kiga	JCOAL
Terry Wall	University of Newcastle
Terutoshi Uchida	IHI
Thomas Paarup Pedersen	Dong Energy
Timothy Fout	US DOE - NETL
Toru Namiki	JCOAL
Toshihiko Yamada	IHI
Toshiomi Higuchi	Air Products Japan Inc.
Tsuyoshi Honda	Mitsui
Valentin Becher	Technische Universität München
Vicente Cortes-Galeano	CIUDEN
Vince White	Air Products PLC
Yasuo Arai	JCOAL
Young Ju Kim	Korea Electric Power Research Institute
Yoshito Yoshimura	JCOAL
Yuji Fukuda Fukuda	Babcock-Hitachi KK
Yuko Yamasaki	JCOAL
Yuzo Shirai	CRIEPI


Yokohama Bridge

3rd Oxy-Combustion Network Meeting

5th-6th March 2008

Yokohama Symposia, Yokohama, Japan

Organised by

IEA Greenhouse Gas R&D Programme
IHI
JCOAL and
JPOWER

4th March 2008

Visit to CREIPI Research Facility

13.00 to 16.30	Meeting Point: Hotel New Grand Reception 13.00
10.15	Pre-Registration, Lobby New Grand Hotel

5th March 2008 Day 1

09.00 to 09.20 Welcome Remarks/Brief Introduction: IHI/JCoal/JPower
09.20 to 09.30 Welcome Response/Administrative Announcement: John Topper IEA GHG

Session 1 Challenges of CCS and Oxy-Combustion—Keynote Address Chair: John Topper, IEA GHG, UK

09.30 to 10.10 CCS Policy and Overview: Makoto Akai, AIST, Japan

10.10 to 10.50 Technical Consideration and Challenges of Oxy-Combustion: Ken Okazaki, TIT, Japan

10.50 to 11.05 Coffee Break

	Session 2a Oxy-Combustion Fundamentals Chair: Klas Andersson, Chalmers, Sweden	**Session 2b** On-going Experimental Studies Chair: John Smart, RWE NPower, UK
11.05 to 11.25	Performance of PF Boilers Retrofitted with Oxy-Coal Combustion: Understanding Coal Burnout, Coal Reactivity, Burner Operation, and Furnace Heat Transfer: T.Wall, Newcastle University, Australia	E.On UK's Pilot Scale Oxy-Fuel Combustion Experience: Development, Testing and Modelling: B. Goh, E.On UK
11.25 to 11.45	Evaluation of Gas Radiation Modelling in Oxy-Fired Furnaces: R. Johansson, Chalmers University Sweden	Fundamental Studies and Pilot Scale Evaluation of Oxy-Coal Firing in Circulating Fluidized Bed Boilers: E. Eddings, University of Utah, USA
11.45 to 12.05	Stabilising Swirl Pulverised Coal Flames Under Oxy-Fuel Conditions: D. Toporov, RWTH Aachen University, Germany	Impact of Combustion Conditions on Emissions Formation (SO2, NO) and Fly Ash Composition: J. Maier, IVD University of Stuttgart, Germany
12.05 to 12.25	Model Validation Studies for Pulverised Coal Jet Ignition in O2/CO_2 Environment: J. Wendt, University of Utah, USA	Technical Consideration of Mercury Emissions in an Oxy-Coal Power Plant with CO_2 Capture: S. Santos - IEA Greenhouse Gas R&D Programme, UK

12.25 to 13.25 Lunch

	Session 2c Oxy-Combustion System Studies Chair: Kevin McCauley, B&W, USA	**Session 2d** On-going Experimental Studies Chair: Takashi Kiga, JCOAL, Japan
13.25 to 13.45	Efficiency Increase of the Oxyfuel Process by Waste Heat Recovery Considering the Effects of Flue Gas Treatment: M. Klostermann, TUHH Germany	Understanding Potential Environmental Impacts of Oxy-Fuel Combustion: C.W. Lee and A. Miller, US EPA, USA
13.45 to 14.05	Consideration for Oxy-Fuel Coal Fired Combustion Power Plant System Integration: H. Hack, Foster Wheeler, USA	High Temperature Reduction of Nitrogen Oxides in Oxy-Fuel Combustion: F. Normann, Chalmers university, Sweden
14.05 to 14.25	3rd Generation Oxy-Combustion Systems: C. Slavador, CANMET, Canada	Understanding the effects of O2 and CO_2 on NOx Formation During Oxy-Coal Combustion: C.R. Shaddix, Sandia Laboratory, USA
14.25 to 14.45	Oxy-Combustion: Research, Development and Systems Analysis: T. Fout, DOE/NETL,	Evaluation of CO_2 Capturing– Repowering System Based on Oxy-Fuel Combustion for Utilising Low Pressure Steam: P.S. Pak, Osaka University, Japan

14.45 to 15.00 Break

Session 3: Oxygen Production and CO_2 Processing Chair: Minish Shah, Praxair, USA

15.00 to 15.20	Phase Equilibria Measurements and their Application for the CO_2 Separation from CO_2 Rich Gases: R. Eggers and D. Kopke, TUHH, Germany
15.20 to 15.40	Purification of Oxy-Fuel Derived CO_2: V. White, Air Products, UK
15.40 to 16.00	Update on Advanced Developments for ASU and CO_2 purification Units for Oxy Combustion: J.P. Trainer, N. Perrin, A Darde, Air Liquide, France
16.00 to 16.20	Consideration for Removal of Impurities from CO_2 Rich Flue Gas of Oxy-Fuel Combustion: M. Anhaden, Vattenfall, Sweden
16.20 to 16.40	Technical Consideration for a Very Large Scale Air Separation for Large Scale Coal Fired Power Plant Application: V. White, Air Products, UK

Session 4: Discussion Forum: Oxygen Production and CO_2 Processing Chair: Jost Wendt, university of Utah, USA

16.40 to 17.30 Mini Panel Discussion

Close Day 2 18.25 Dinner—Cruise round Yokohama Bay

6th March 2008 Day 2

Session 5: Future of Oxy-Coal Combustion Chair: Prof. Keiji Makino, IHI, Japan

09.00 to 09.30 — Vattenfall Schwarze Pumpe Pilot Plant: Dr Marie Anheden, Vattenfall R&D AB, Sweden

09.30 to 09.45 — APP Project: Overview of Oxy-Fuel Working Group—A Platform for Cooperation: Terry Wall, University of Newcastle, Australia

09.45 to 10.05 — Oxy-Combustion Activities at Tsinghua University: CO_2 Capture Based on Chemical Looping: Ningsheng Cai, Tshingua University, China

10.05 to 10.25 — Capture Ready Plant Concept: Retrofitting Power Plant with Oxy-Combustion: John Davison, IEA GHG, UK

10.25 to 10.45 Break

Session 6: Large Scale Burner and Boiler Development—Technology and Equipment Manufacturer Perspective Chair: Chris Spero, CS Energy, Australia

10.45 to 11.05 — Recent Test Results on Oxy-Fuel Combustion Using the Pilot-Scale Test Facilities: T. Uchida, T. Yamada, K. Hashimoto, S. Watanabe; IHI, Japan

11.05 to 11.25 — Scale Up of Oxy-Coal Combustion at B&W's 30MWth SCDF: H. Farzan and K. McCauley, Babcock and Wilcox, USA; R.Varagani, Air Liquide, USA

11.25 to 11.45 — Alstom Development of Oxy-Fired PC and CFB Power Plants: J. Marion, Alstom Power, USA

11.45 to 12.05 — Oxy-Combustion UK Project Update: Development of 40MWth Burner Testing Programme: D. Fitzgerald, Doosan Babcock, UK

12.05 to 12.25 — Jupiter Oxygen—15 MWth Oxy-Combustion Boiler Test Results: B. Patrick, Jupiter Oxygen, USA

12 to 13.40 Lunch

Session 6: Large Scale Demonstration and Pilot Scale Projects Chair: Sho Kobayashi, Praxair, USA

13.40 to 16.00 — Panel Discussion — Panel members: Marie Anheden, Vattenfall, Sweden
Frank Kluger, Alstom power, Germany
Claude Prebende, TOTAL, France
Chris Spero, CS Energy, Australia
Vicente Cortez Galeano, CUIDEN, Spain
Jong Soo Kim, KIST, Korea
Minish Shah, Praxair, USA
Dante Bonaquist, Praxair, USA

P1 — Callide Oxy-Fuel Project—Technical Evaluation of the Oxy-Combustion and CO_2 Capture System Design: C. Spero, T. Yamada, E.Sturm and D. McGregor, CS Energy, Australia and IHI, Japan

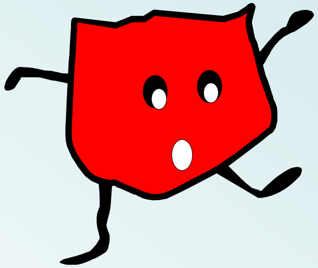
P2 — The CO_2 Pilot at Lacq: An Integrated Oxy-Combustion CO_2 Capture and Geological Storage Project: N. Aimard and C. Prebende, TOTAL, France

P3 — Test Facilities for Advanced Technologies for CO_2 Abatment and Capture in Coal Power Generation: V. Cortes, CUIDEN, Fundacion Estata Cuidad de la Energia, Spain

P4 — Oxy-Combustion Research Activities in S. Korea—Overview to the Youngdong 100MWe Oxy-Combustion Power Station Project Development: J. S. Kim, KIST, Korea

P5 — Oxy-Coal Combustion Demonstration Project: D. Bonaquist, R. Victor, M. Shah, H. Hack, A. Hotta, D. Leathers, Praxair, USA; Foster Wheeler, USA/Finland; and Jamestown Board of Public Utilities

Close Day 2

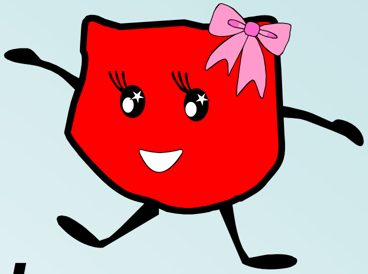


3rd Workshop
IEAGHG International Oxy-Combustion Network
Yokohama, Japan

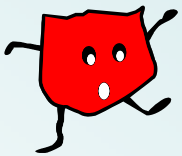
Approach to Oxy-Fuel Combustion

5th March, 2008

Toru Namiki
President
Japan Coal Energy Center, JCOAL



For the Best Mix of Energy Sources



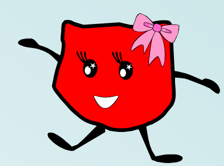
Renewable

Nuclear

Oil

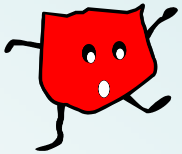
Natural Gas

Coal

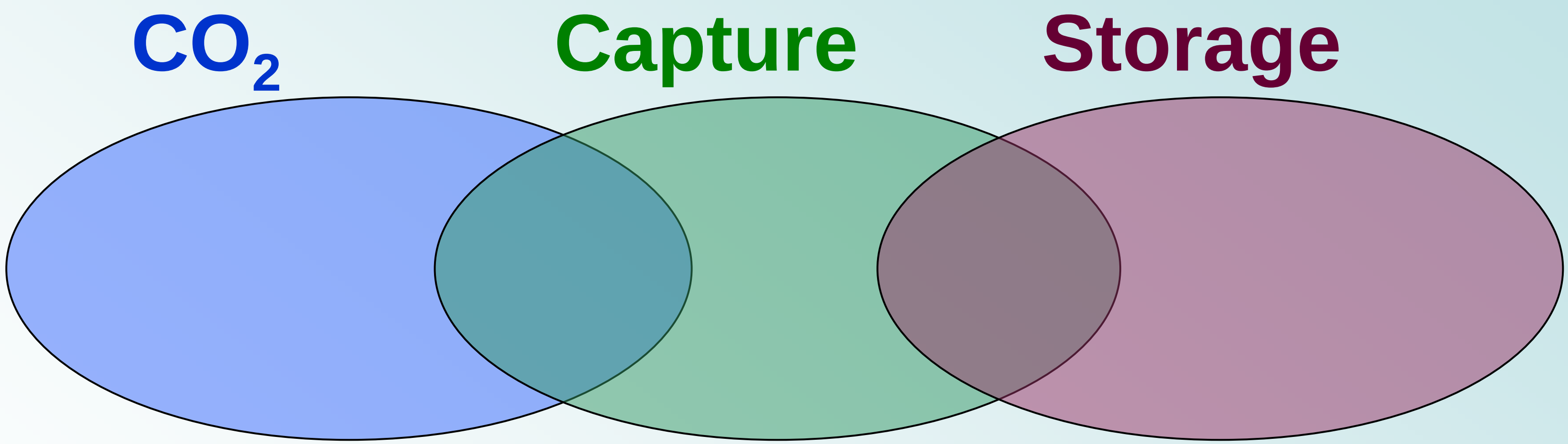


Even though more amount of CO2 would be emitted from coal, so as to keep the situation of best mix of energy sources, technologies to reduce CO2 must be developed, demonstrated and actually applied.

CCS, Carbon Dioxides Capture & Storage



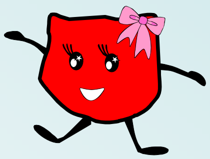
CCS technology we are expecting to be applicable not only to newly installed plants but also to existing ones in the near future is Oxy-fuel Combustion.



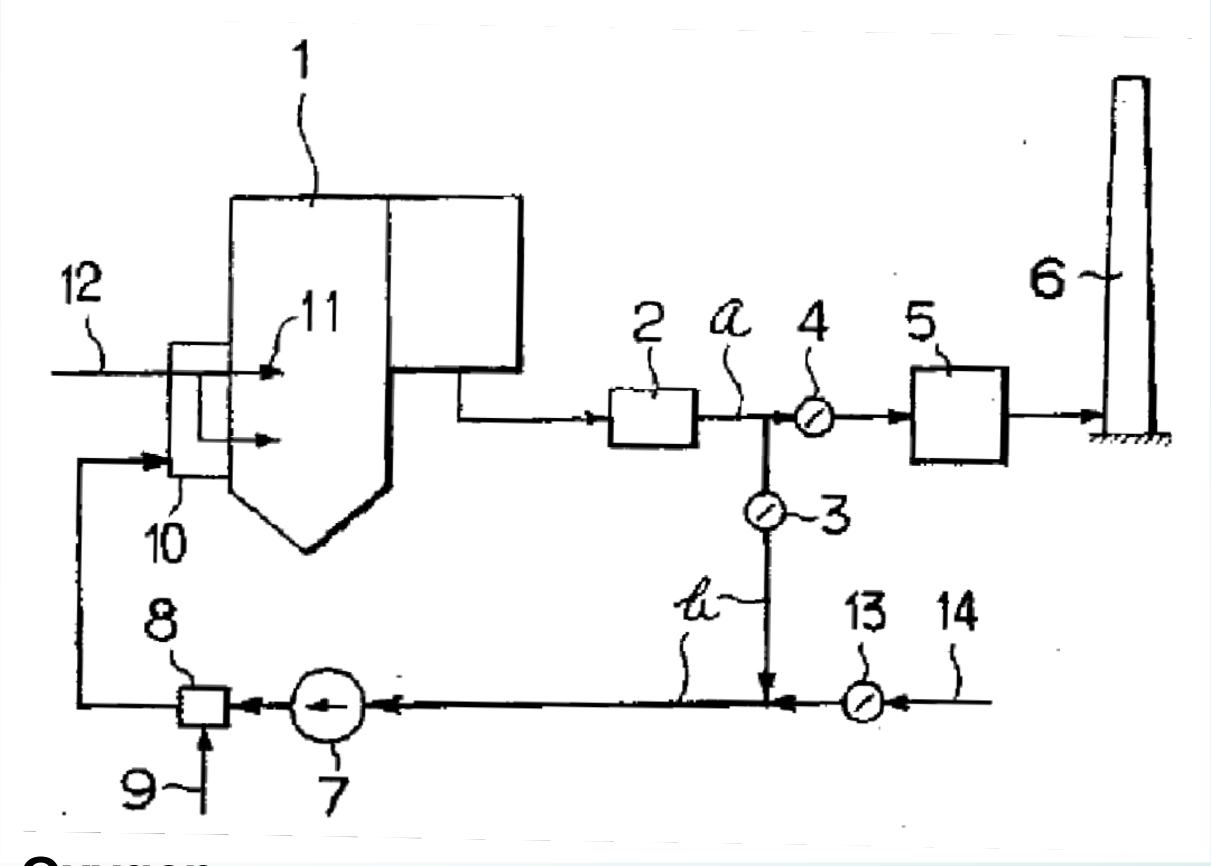
Coal effectively and most commonly used in pulverized coal firing boilers

Oxy-fuel Combustion technology

Every kind of option



Technology Development



Oxygen

(Source: Yokohama city HP)

Thank you for your attention!

International Network for Oxy-Combustion with CO_2 Capture

Introduction to 3rd Workshop

Yokohama, Japan

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

IEA Greenhouse Gas R&D Programme

OPEC Organization of the Petroleum Exporting Countries

ALSTOM B&W BG GROUP bp Chevron

Eni EniTecnologie e·on EPRI ExxonMobil REPSOL YPF

RWE Schlumberger Statkraft STATOIL TOTAL VATTENFALL

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

Earlier 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.
- 2nd Workshop was hosted by Alstom in Windsor, Ct, USA
  - It was attended by 88 participants from 16 Countries
- Reports and/or copies of presentations can be obtained at our website:

http://www.co2captureandstorage.info/networks/oxyfuelmeetings.htm

At this Meeting

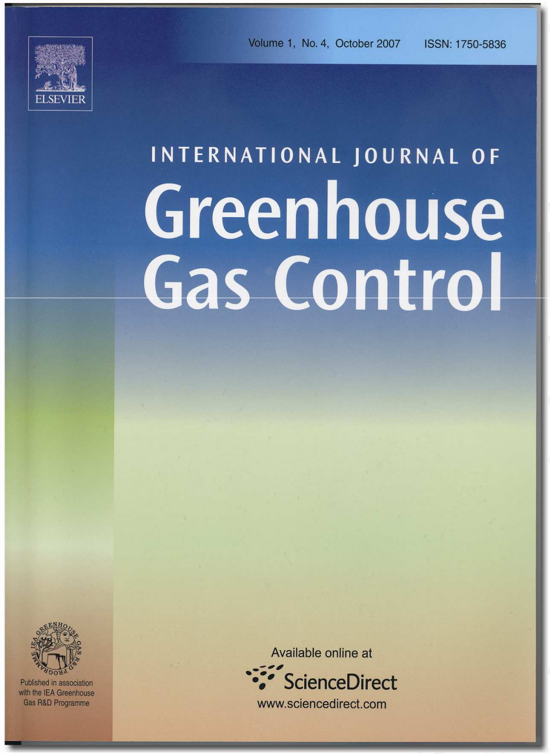
- We have had to close registration list early because of the demand – about 105 people are attending
- Excluding participants from Japan, breakdown of participants shows that there are:
  - 19 participants from N. America
    - 2 persons from Mexico
  - 37 from Europe
  - 10 from Asia
    - 6 persons from S. Korea
    - 2 from India
    - 1 from China
    - 1 from Philippines
  - 5 from Australia
- Participants from 18 different countries are present today
- Excellent networking

Today: Housekeeping Points

- Coffee breaks around 10.50 and 14.45
- Lunch at 12.25
- Session 02 – Rooms Assignment
  - Sessions 2b and 2c at Main Room
  - Sessions 2a and 2d at Second Room
- Afternoon session will finish at around 17.30
- Dinner this evening is during a Cruise around Yokohama Bay –
  - **please be at the meeting point indicated on your location map at 18.10.**
- **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

IEA Greenhouse Gas R&D Programme

IEA Greenhouse Gas R&D Programme



7th INTERNATIONAL CONFERENCE ON GREENHOUSE GAS CONTROL TECHNOLOGIES

GHGT-9

16th – 19th November 2008

Washington D.C.

http://mit.edu/ghgt9

CALL FOR PAPERS CLOSES 28th MARCH 2008

Acknowledgement

- Thanks to IHI, JCoal and JPower for local organisation and for workshop dinner arrangement.

- And thanks to CRIEPI for the facility visit.

CCS Policy Development in Japan

IEA-GHG 3rd MEETING of the

OXY-FUEL COMBUSTION NETWORK

5 March 2008

Yokohama Symposia, Yokohama, Japan

Makoto Akai, AIST

Contents

- Background
  - Technical R&D
  - Research on non-technological aspects
- R&D to policy agenda
  - Development of regulatory framework by the Ministry of Environment
  - Advisory committee on CCS under METI
- Prime Minister's "Cool Earth 50" initiative
- Conclusions

Technical R&D on CCS in Japan

- **Late 80's - :**
  - Proposal of the concept of CCS including various capture technologies including post-combustion, pre-combustion and oxy-fuel.
- **Early 90's - :**
  - Independent research activities in National Labs., Electric Utilities, Universities, etc.
  - Comprehensive feasibility study on performance and cost analysis
- **Mid 90's - :**
  - Establishment of R&D projects under METI (former MITI)

METI's Technical R&D Program on CCS (1997 -)

Diversified portfolio approach considering the storage potential, risk, etc.

- CO_2 capture
  - Development of chemical absorbent and membrane; Application to ironworks; Oxy-fuel; etc.
- Ocean sequestration (1997 -)
  - Focused on environmental assessment and development on near-zero impact technology
- Geological storage (2000 -)
  - Nagaoka project
    - Injected CO_2: 10,405 t (2003 - 2005)
- ECBM (2000 -)
  - Yubari project

M. Akai, AIST

Non-technical R&D

- **Public perception**
  - Identification of public's concern and development of communication strategy
- **Accounting**
  - National Inventory and Project Based Accounting
  - Contribution to develop 2006 IPCC Guideline
- **Applicability to CDM**
  - Submission of two new methodology to CDM-EB
- **Confidence building on CCS**
  - Risk assessment, communication strategy,etc.

Toward a Policy Agenda

Recent Progress on Regulatory Framework for Sub-seabed Storage of Captured CO_2

Background

- **In conjunction with the amendment of Annex I to the London Protocol 1996, Japan schedules to amend *Law Relating to the Prevention of Marine Pollution and Maritime Disaster* in order to manage and implement Carbon Dioxide (CO_2) sequestration in sub-seabed geological formations in an appropriate manner.**

M. Akai, AIST

Recent Development

September 25, 2006

- **Environment Minister consulted Central Environment Council about the utilization of the sub-seabed CCS to help prevent climate change and on the framework for regulating SS-CCS to protect marine environment.**

February 20, 2007

- **The Council submitted the report to the Minister.**

March 9, 2007

- **Based on the Council report, GOJ(MOEJ) drafted the bill on the revision of Marine Pollution Control Law, and submitted to the Diet.**

May 23, 2007

- **The bill was adopted by the Diet (promulgated on May 30).**

Permit from Minister of the Environment

- **Any party who plans to conduct CO_2 Storage to Sub Seabed Formation (CS-SSGF) shall submit application document including, but not limited to, the implementation plan, the environmental impact assessment and the monitoring plan, and shall obtain a fix-term permit from the Minister of the Environment.**
- **The Minister of the Environment issues the permit to the applicant only when:**
  1. **Proposed site and method of the CS-SSGF do not cause any adverse effects on the marine environment where the CS-SSGF takes place; and**
  2. **No other appropriate disposal methods are available.**

Application range of the framework

- **In the event of a CO_2 leak, its impact on the marine environment will be the same regardless of the pathway or method of CO_2 injection into sub-seabed geological formations.**
- **Therefore, CS-SSGF with direct access from on-shore, which is excluded from definition of "dumping" in the London Protocol 1996, is also subject to this provision and shall obtain a permit from the Minister of the Environment.**

Term of permit and its renewal

- **The permit is issued for a maximum period of five years.**
- **The Minister of the Environment will consider the renewal of the permit taking the state of operation and the possible impact on the environment into consideration.**

Site-selection criteria

- **Any party who plans to conduct CS-SSGF shall evaluate migration of CO_2 and leakage pathways, by reservoir simulations or other appropriate methods, based on the geological/hydrological features of the site.**
- **The party shall prove:**
  1. **that the stability/integrity of storage is guaranteed;**
  2. **that the capacity of reservoir is large enough compared to the total anticipated volume of the CO_2 steams; and**
  3. **that appropriate mitigation measures are available in the event of a leak.**

Consideration of reducing disposal amounts of CO_2 and other disposal options

- **Under the current regulatory framework on disposal into the sea of wastes and other matter from vessels, etc. , further attempts to reduce the necessity for disposal into the sea are required before disposal into the sea, based on WAF.**
- **In the case of CS-SSGF, the practical regulatory framework will be discussed, based on conditions to be included in CO2-WAG.**

M. Akai, AIST

Action list concerning the concentration of CO_2 and impurities in a CO_2 stream

The amended Annex I to the London Protocol 1996 stated that CO_2 streams to be considered for dumping consist overwhelmingly of CO_2. In addition, Annex II requires developing a national Action List to provide a mechanism for screening, which in principle bans dumping if it is not in compliance.

- **In the case of CS-SSGF in Japan, the numerical limits are to be established in order to judge if CO_2 streams consist overwhelmingly of CO_2, and to confirm absence of high concentration of toxic substances such as sulfur dioxide.**
- **Those numerical limits and necessary criteria will be determined later in consideration with the international trends.**

Specific Guidelines

Government ordinance (7 Sep. 2007)

- **Quality of CO_2 streams (Action List)**
  1. **CO_2 should be captured by chemical reaction using amines**
  2. **CO_2 concentration should be > 99 vol%**
     - **> 98 vol % if captured from hydrogen production in oil refinery**
  3. **CO_2 stream should not include wastes or other matter for the purpose of disposing of those wastes or other matter**

Assessment of potential effects on the marine environment in the event of a leak

- **Any party who plans to conduct CS-SSGF shall submit an impact assessment report to address potential impacts in the event of a leak, as stated in CO2-WAG. Main items of the assessment are described below.**
  1. **Characterization of CO_2 streams to be disposed into a sub-seabed geological formation**
  2. **Leakage case scenarios with its location and amount of leakage**
  3. **Description of the current marine environment including marine life**
  4. **Simulation results of possible changes in the marine environment and assessment of its impact, based on the leakage case scenarios**
- **The Minister of the Environment examines the impact assessment report, and issues a permit only when the minister confirms that the CCS has no potential risks to the marine environment.**

Monitoring

- **Monitoring:**
  - to verify that no CO_2 leaks from the reservoir,
  - to know the possible changes in the marine environment.
- **Monitoring plan shall be submitted as a part of application documents for the review by the Minister of the Environment.**
  - Required not only for the duration of injection, but also after the cease of injection (post closure).
- **The actual period of the post closure monitoring is left for future solution**
- **The party conducting CS-SSGF is required to report the monitoring results periodically to the Minister of the Environment.**

Response to the potential impact on the marine environment

- In case monitoring results indicate that CO_2 migration or impact on the marine environment does not stay within the range of assessments, the party shall take corrective actions.
- If this is the case, the party shall immediately inform the Minister of the Environment of the monitoring results and the planned corrective actions.
- The party is also required to report on the implementation of the actions as well as subsequent periodical monitoring results.

Development of Guidelines

- **With this amendment, the regulatory framework for CS-SSGF was established in accordance with Annex II (WAF) to the London Protocol 1996.**
- **Specific Guidelines for the Assessment of Carbon Dioxide Streams for Disposal into Sub-seabed Geological Formations have been developed.**

METI
From R&D towards a Policy Agenda

- **Until recently, CCS has been discussed under the environmental R&D policy in METI**
- **Agency for Natural Resources and Energy, Ministry of Economy, Trade and Industry discussed CCS in the development of *Energy Technology Vision 2100* released in 2005.**
- ***New National Energy Strategy* (2006) and revised *Basic Plan on Energy* (2007) refers to CCS**

METI - Advisory Committee on CCS Policy (October 2006 to October 2007)

Conclusions and recommendations:

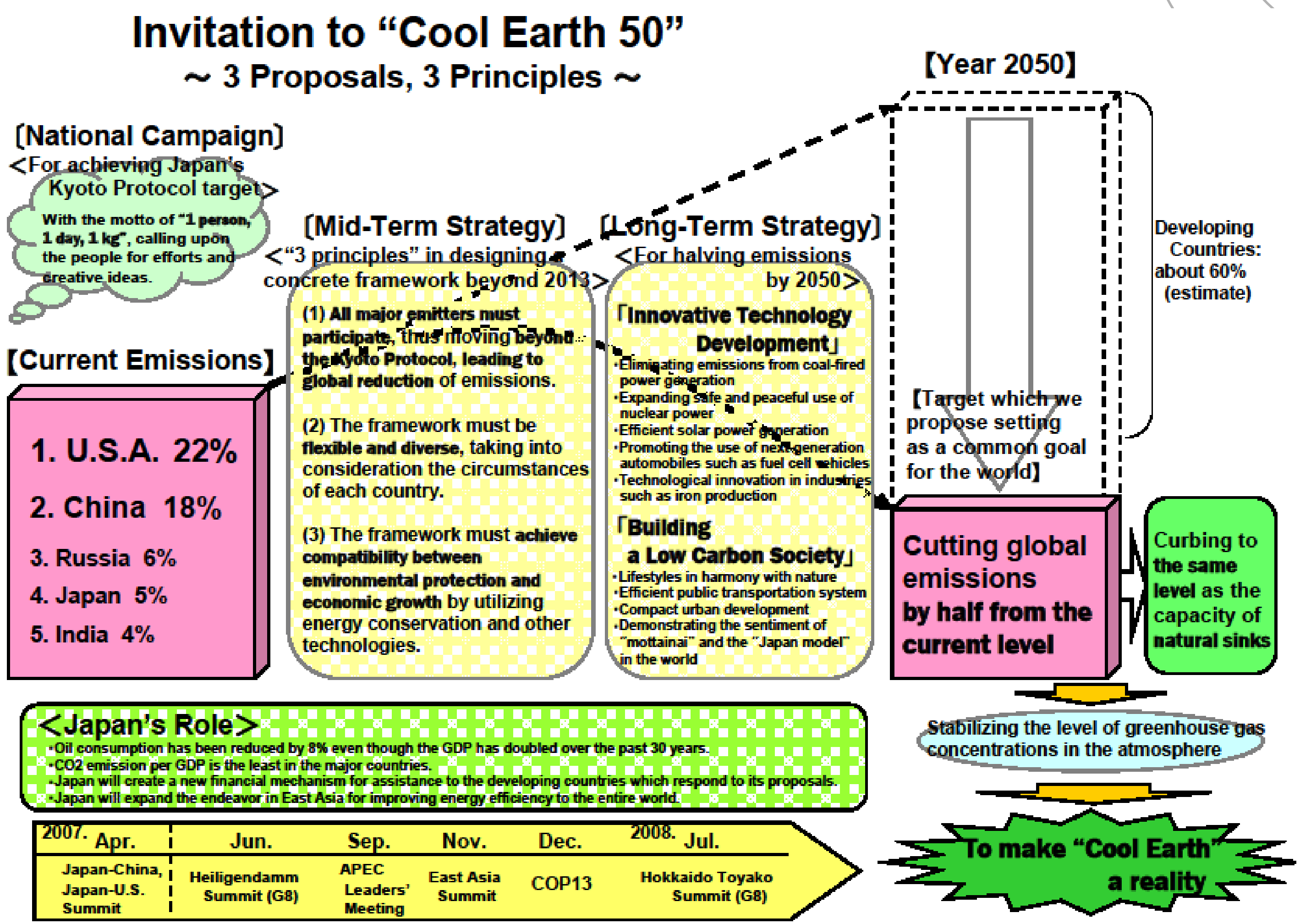
- **Recognizing,**
  - CCS is an important policy option to mitigate climate change
  - In general, there is no economic incentive and economic burden is extremely great
- **Recommend**
  - To carry out R&D on innovative technologies
  - To conduct larger scale demonstration
  - To make proposal on the business environment to facilitate the introduction of CCS

M. Akai, AIST

Response to the Recommendation by the Advisory Committee on CCS Policy

- R&D on innovative technologies
  - On-going R&D, Cool earth initiative
- Larger scale demonstration
  - Under discussion
- Business environment (socio-economic system)
  - Legal and institutional issues
    - Business law, long term liability, accounting, etc.
  - Financial issues and business model
    - Incentives, business insurance, etc.
  - Confidence building

Prime Minister's "Cool Earth 50" Initiative



M. Akai, AIST

Innovative Technologies for Significant Reductions of CO_2 Emissions

1. Innovative Zero-emissions Coal-fired Power Generation

The combination of the efficiency improvements of coal gasification power generation and CO2 capture and storage (CCS) technology to realize zero-emissions coal-fired power generation, which currently accounts for around 30% of the global emissions

2. Advanced Reactors for Nuclear Power Generation

The development and commercialization of next generation light water reactors, small and medium reactors, high temperature gas-cooled reactors, and fast breeder reactors (FBR) to significantly increase zero-emissions nuclear power generation

3. Innovative Technology for High-efficiency and Low-cost Solar Power Generation

A significant improvement in the efficiency of solar power generation to reduce its cost to the level of thermal power generation, together with the capacity increase and cost reduction of rechargeable batteries

4. Innovative Technology for the Use of Hydrogen

The cost reduction and efficiency improvements of fuel cells for the wide use of fuel cell vehicles to realize zero emissions in the automobile sector, which currently accounts for nearly 20% of the global emissions

5. Ultra High Energy Efficiency Technology

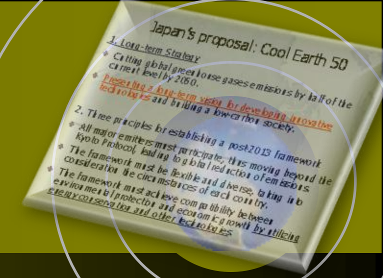
Ultra high energy efficiency technologies for production processes and equipment to realize significant energy saving and emission reductions, e.g. iron and steel making technology to partially substitute hydrogen for coke as a reducer

Cool Earth – Innovative Energy Technology Program

5 March 2008
Ministry of Economy, Trade and Industry

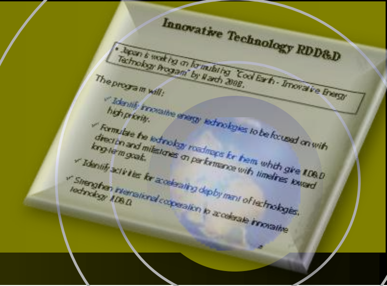
Prepared for IEA/CERT meeting. Courtesy of Mr. Shirai (METI)

Japan’s proposal:
Cool Earth 50



1. **Long-term Strategy**
   – Cutting global greenhouse gases emissions by half of the current level by 2050.
   – Presenting a long-term vision for developing innovative technologies and building a low-carbon society.
2. **Three principles for establishing a post-2013 framework**
   – All major emitters must participate, thus moving beyond the Kyoto Protocol, leading to global reduction of emissions.
   – The framework must be flexible and diverse, taking into consideration the circumstances of each country.
   – The framework must achieve compatibility between environmental protection and economic growth <u>by utilizing energy conservation and other technologies.</u>

Innovative Technology RDD&D



- Japan is working on formulating "Cool Earth - Innovative Energy Technology Program" by March 2008.

The program will:

- Identify innovative energy technologies to be focused on with high priority.
- Formulate the technology roadmaps for them, which give RD&D direction and milestones on performance with timelines toward long-term goals.
- Identify activities for accelerating deployment of technologies.
- Strengthen international cooperation to accelerate innovative technology RD&D.

Identifying Key Innovative Energy Technologies in Key Sectors: 21 Candidates

Efficiency improvement | ***Low carbonization***

Oil | LNG | Coal | Nuclear Power | Biomass | Solar | Wind

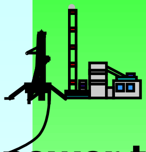
Supply side

Electric Power

Efficient coal-fired power plant

Efficient LNG-fired power plants

CCS



Innovative solar power

Advanced nuclear power

Superconducting power transmission

Demand side

Transport

ITS

FCV

PHEV/EV

Biofuel

Industry

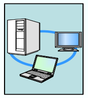
Innovative materials/ manufacturing process

Steel making process with Hydrogen

Residences/ Buildings

Efficient houses/buildings

Efficient lighting



Fuel Cell for residential use

Efficient Heat pumps

Efficient IT devices/networks

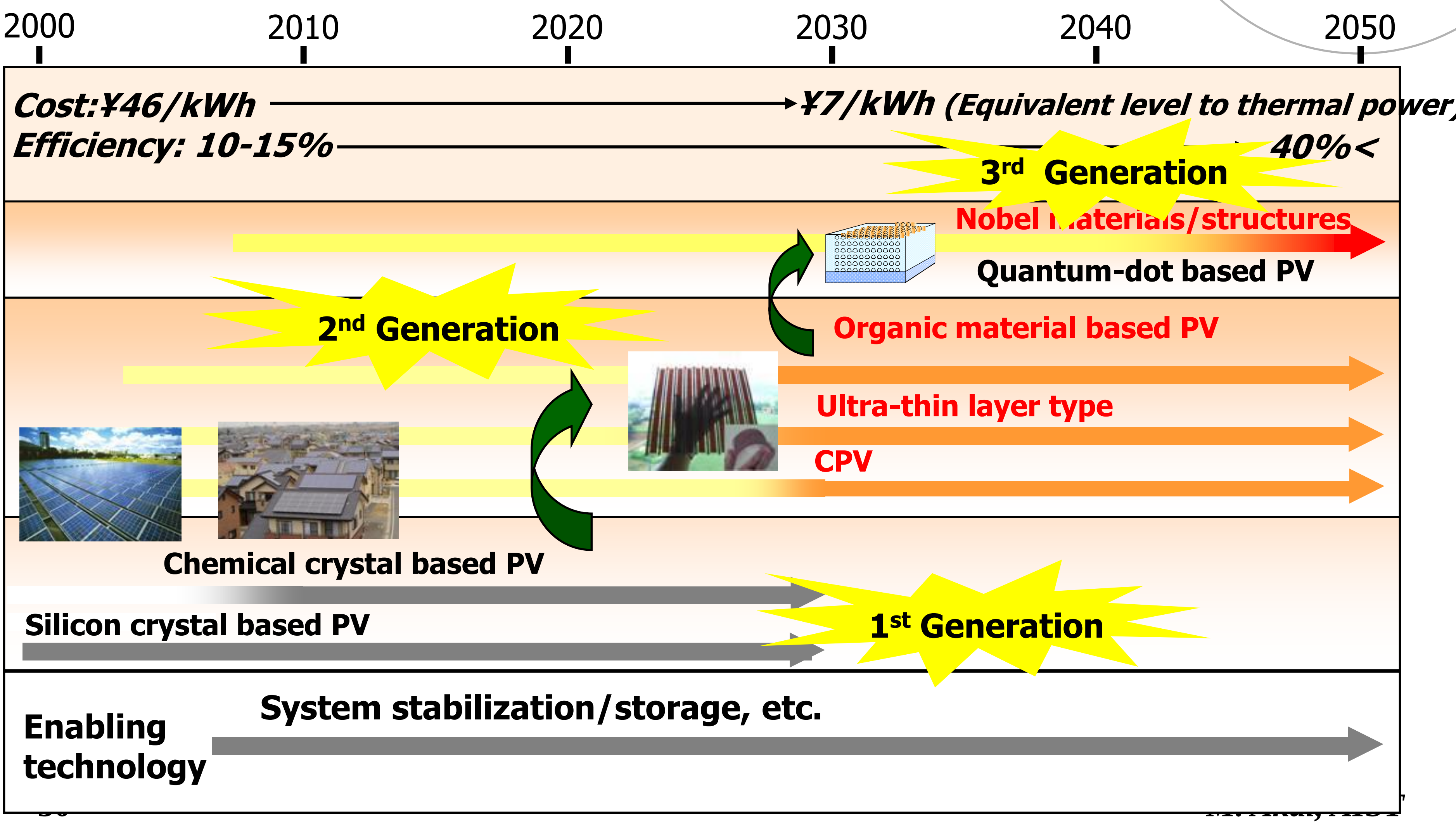
HEMS/BEMS/Regional EMS

Cross sectroral

Power storage | **Power electronics** | **Hydrogen production/storage/ transport** | **CCS (restated)**

Formulating technology roadmaps toward 2050 to coordinate global RD&D

An image of our technology roadmap for innovative solar power generation



Accelerating global RDD&D

- **It is essential to secure substantial investment to develop innovative technologies.**
- **A long-term strategy is necessary to promote investment.**

The EU, U.S. and Japan have already taken substantial steps:

"Europe Strategic Energy Technology Plan" (2007)

"Climate Change Technology Plan" (2006)

"Energy Technology Strategy" (2007)
"Cool Earth -Innovative Energy Technology Program" (coming soon)

"Energy Technology Perspective 2008" (coming soon)

Share the long-term roadmaps of energy technologies to accelerate global technology RDD&D.

International Cooperation (1)

- Technology Roadmaps -

How can technology roadmaps help ensure the efforts leading to the long-term goal?

- ⇒ ***Underpin the technology strategy to achieve long-term goal by clarifying technology milestones/challenges to overcome***
- ⇒ ***Promote long-term, coherent investment in energy technology to address climate change by clarifying the technology direction***
- ⇒ ***Ensure global efforts through reviewing technology progress based on the roadmaps***
- ⇒ ***Identify areas of focus where further global efforts or cooperation is needed***
- ⇒ ***Implement the international cooperation through existing partnerships/IEA's implementing agreements***

M. Akai, AIST

International Cooperation (2)

- Deepen the collaboration through existing partnerships -

- ***Build upon existing international frameworks***
- ***Explore areas where further global efforts are needed***
- ***Enhance cross-linking among projects***

- **Near-zero emission coal, CCS: FutureGen, CSLF, APP**
- **Nuclear: GNEP, GIF**
- **Fuel Cells: IPHE**
- **Others: Implementing agreements in IEA**

(Photos provided by each organization's HP)

M. Akai, AIST

Summary

- **CCS is now became an agenda for energy and environmental policy, however … there still exist needs for**
  - **Significant cost reduction**
  - **Incentives including appropriate "mechanisms"**
  - **Confidence by public, scientists and policy makers**

and … if CCS is inevitable for Japan's policy

  - **Responsible body promoting ~~RD~~&DD**

- **Political Will as a key driver!**

Towards the Future

- **Difficulties in implementing large scale CCS are becoming obvious**
  - **Cancellation of proposed projects, Re-structuring of FutureGen, etc.**
  - **Public awareness, etc.**

- **Extended and enhanced cooperation should be essential**
  - **International or inter-projects**
- **IEA-GHG would be the core body of such cooperation**

Technical Consideration and Challenges of Oxy-Pulverized Coal Combustion

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3rd Workshop

IEA GHG International Oxy-Combustion Network

March 5-6, 2008, Yokohama Symposia

The Global Warming is obviously accelerated !

The 4th IPCC Report (Feb.2, 2007)
- **Past 100 years**
  temp. rise : 0.74 C (> 0.6 C in the 3rd report)
- **The end of 21st century (without active measures)**
  temperature rise : 6.4 C
  sea level rise : 59 cm

"*Stop the global warming*" is urgent issue, but not so easy.
- **Global warming is due to a huge amount of CO_2 emissions.**
- **Net amount of CO_2 reduction is most important.**
- **Contributions by renewable energies are negligibly small at present.**
- **We have to depend on fossil fuels for a while with CCS.**
- **Only energy-saving or high-efficiency is definitely not enough.**

Clearwater Coal Conference, June 10-14, 2007

concentrated on oxy-firing of coal for CO_2 capture

The Power of Coal

Proceedings of
The 32nd International Technical Conference on
Coal Utilization & Fuel Systems
June 10 – 15, 2007
Sheraton Sand Key Clearwater, Florida, USA

The Clearwater Coal Conference

Oxy-Coal Combustion

	Presentations
2004	No presentation
2005	One presentation
2006	One session
2007	Full sessions (full of audience)

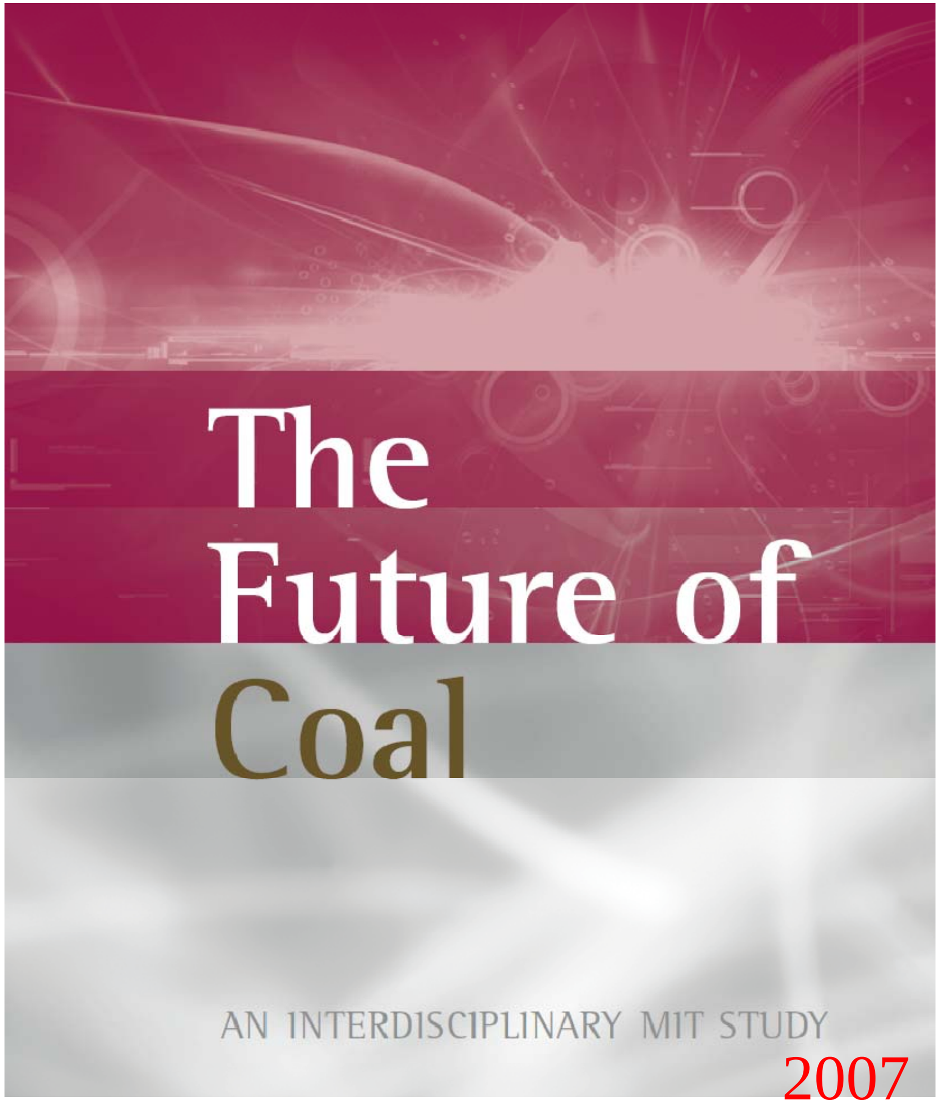
Panel: Oxy-Fuel Technology

Oxy-Fuel I: Overview & New Developments

Oxy-Fuel II: Oxy-Fuel vs. Air Combustion

Oxy-Fuel III: Pressurized Oxy-Fuel Combustion System

Oxy-Fuel IV: CFB Oxy-Fuel Combustion and Oxy-Fuel Burner



OPTIONS FOR A CARBON-CONSTRAINED WORLD

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BOX 1 ILLUSTRATING THE CHALLENGE OF SCALE FOR CARBON CAPTURE

- Today fossil sources account for 80% of energy demand: Coal (25%), natural gas (21%), petroleum (34%), nuclear (6.5%), hydro (2.2%), and biomass and waste (11%). Only 0.4% of global energy demand is met by geothermal, solar and wind.[1]
- 50% of the electricity generated in the U.S. is from coal.[2]
- There are the equivalent of more than five hundred, 500 megawatt, coal-fired power plants in the United States with an average age of 35 years.[2]
- China is currently constructing the equivalent of two, 500 megawatt, coal-fired power plants per week and a capacity comparable to the entire UK power grid each year.[3]
- One 500 megawatt coal-fired power plant produces approximately 3 million tons/year of carbon dioxide (CO_2).[3]
- The United States produces about 1.5 billion tons per year of CO_2 from coal-burning power plants.
- If all of this CO_2 is transported for sequestration, the quantity is equivalent to three times the weight and, under typical operating conditions, one-third of the annual volume of natural gas transported by the U.S. gas pipeline system.
- If 60% of the CO_2 produced from U.S. coal-based power generation were to be captured and compressed to a liquid for geologic sequestration, its volume would about equal the total U.S. oil consumption of 20 million barrels per day.
- At present the largest sequestration project is injecting one million tons/year of carbon dioxide (CO_2) from the Sleipner gas field into a saline aquifer under the North Sea.[3]

Notes

1. IEA Key World Energy Statistics (2006)
2. EIA 2005 annual statistics (www.eia.doe.gov)
3. Derived from the MIT Coal Study

(from FOREWARD)

Our audience is government, industry and academic leaders and decision makers interested in the management of the interrelated set of technical, economic, environmental, and political issues that must be addressed in seeking to limit and to reduce greenhouse gas emissions to mitigate the effects of climate change. Coal is likely to remain an important source of energy in any conceivable future energy scenario. Accordingly, our study focuses on identifying the priority actions needed to reduce the CO_2 emissions that coal use produces. We trust that our integrated analysis will stimulate constructive dialogue both in the United States and throughout the world.

This study reflects our conviction that the MIT community is well equipped to carry out interdisciplinary studies of this nature to shed light on complex socio-technical issues that will have major impact on our economy and society.

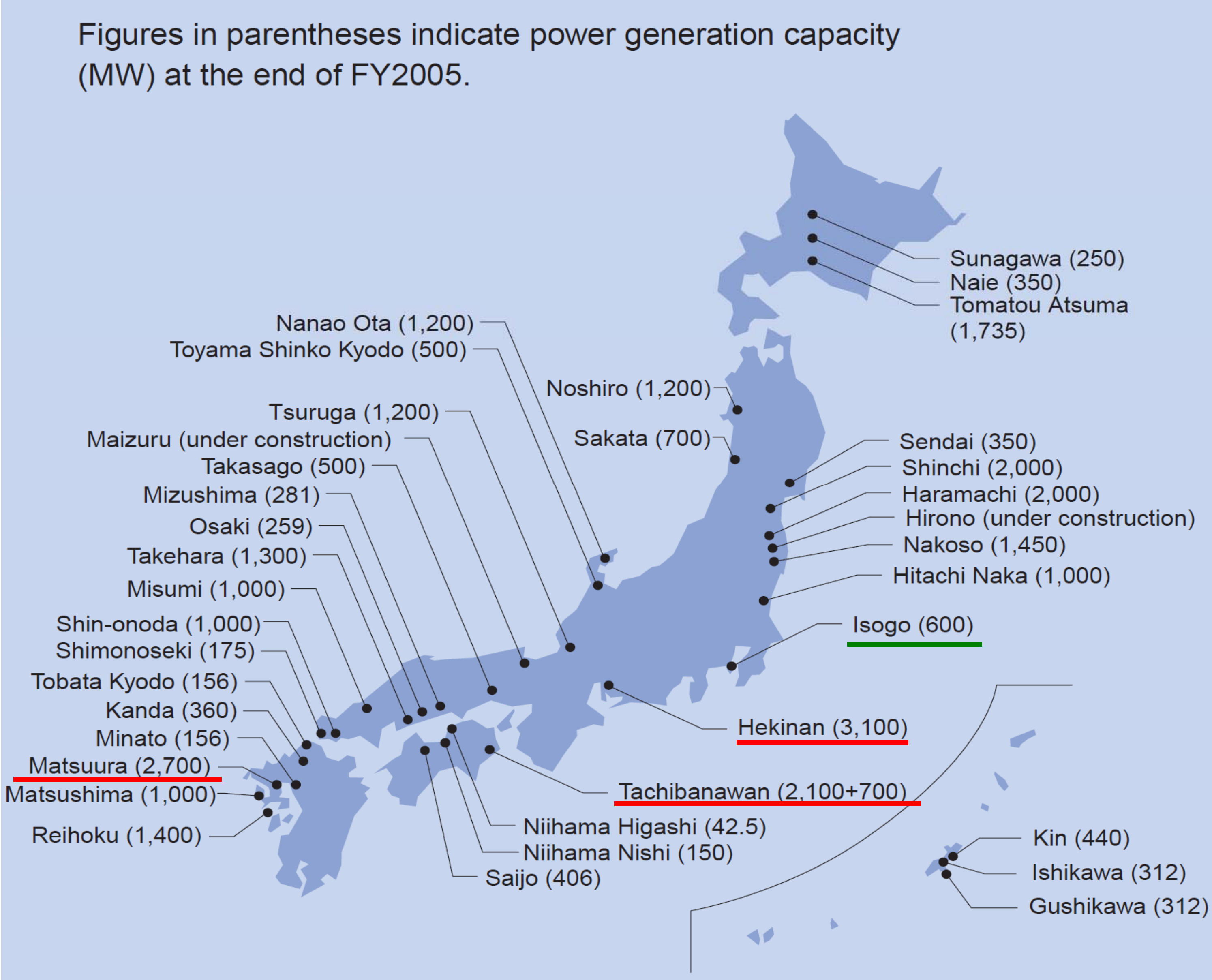
(from EXECUTIVE SUMMARY)

We conclude that CO_2 capture and sequestration (CCS) is the critical enabling technology that would reduce CO_2 emissions significantly while also allowing coal to meet the world's pressing energy needs.

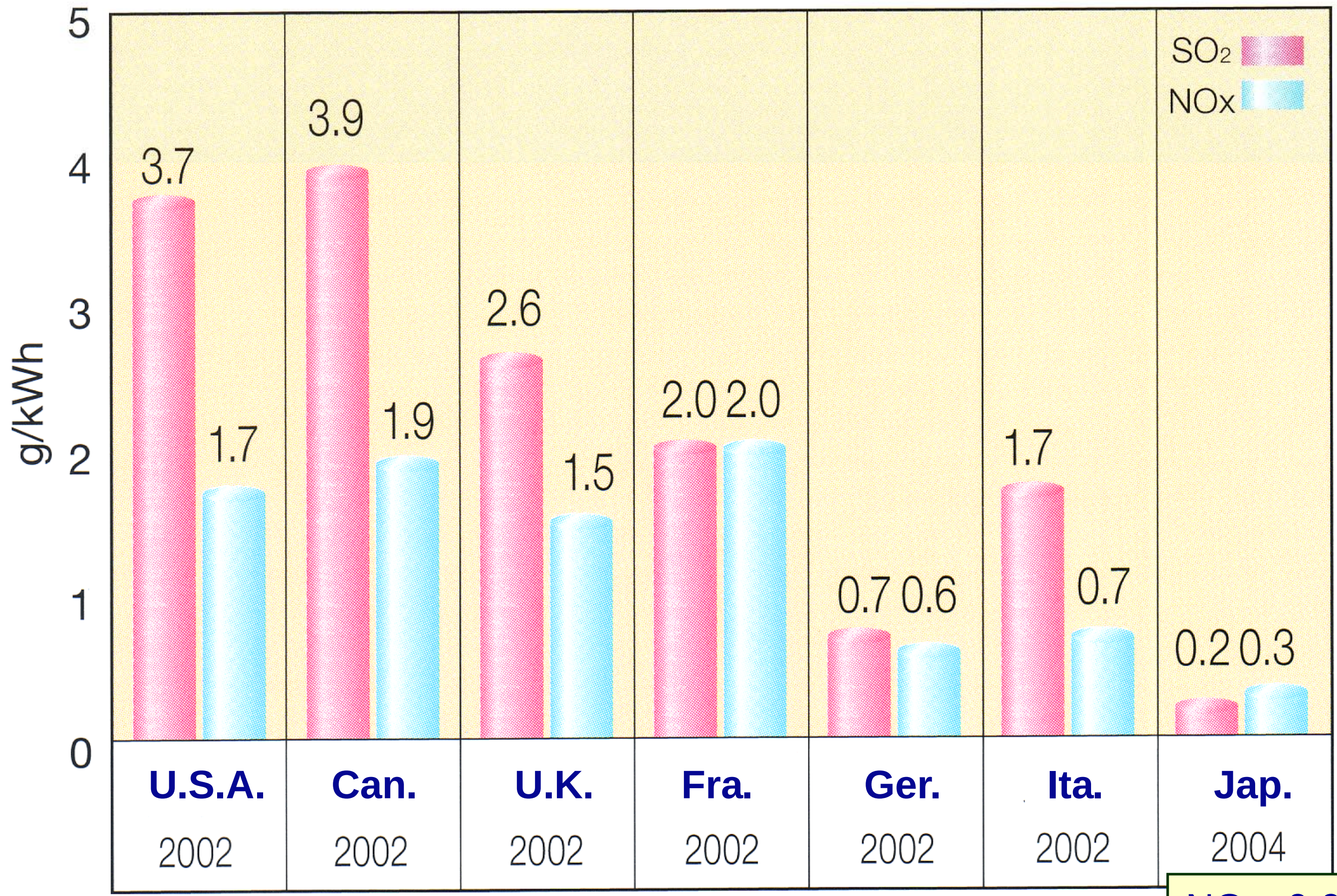
Outline

- Japan's Status of Coal-fired Power Plants
- World Trend of CO_2-free Clean Coal Technology
- O_2/CO_2 (Oxy-firing) Coal Combustion
  - easy CO_2 recovery without separation process
  - drastic NOx reduction and its mechanism
  - further NOx reduction by heat recirculation
  - high in-furnace desulfurization efficiency
  - Flame propagation velocity in high CO_2 conc.
  - Australia/Japan Oxy-firing Project
- IGCC and IGFC with CO_2 Recovery
  - high CO_2 recovery rate and high net efficiency
- CO_2 Sequestration Methodology
- Concluding Remarks

Coal-Fired Power Plants in Japan



Present Status of Clean Coal Technology



NOx: 0.017, SOx: 0.070 (Isogo No.1)

NOx and SOx emissions from fossil fuel fired power stations

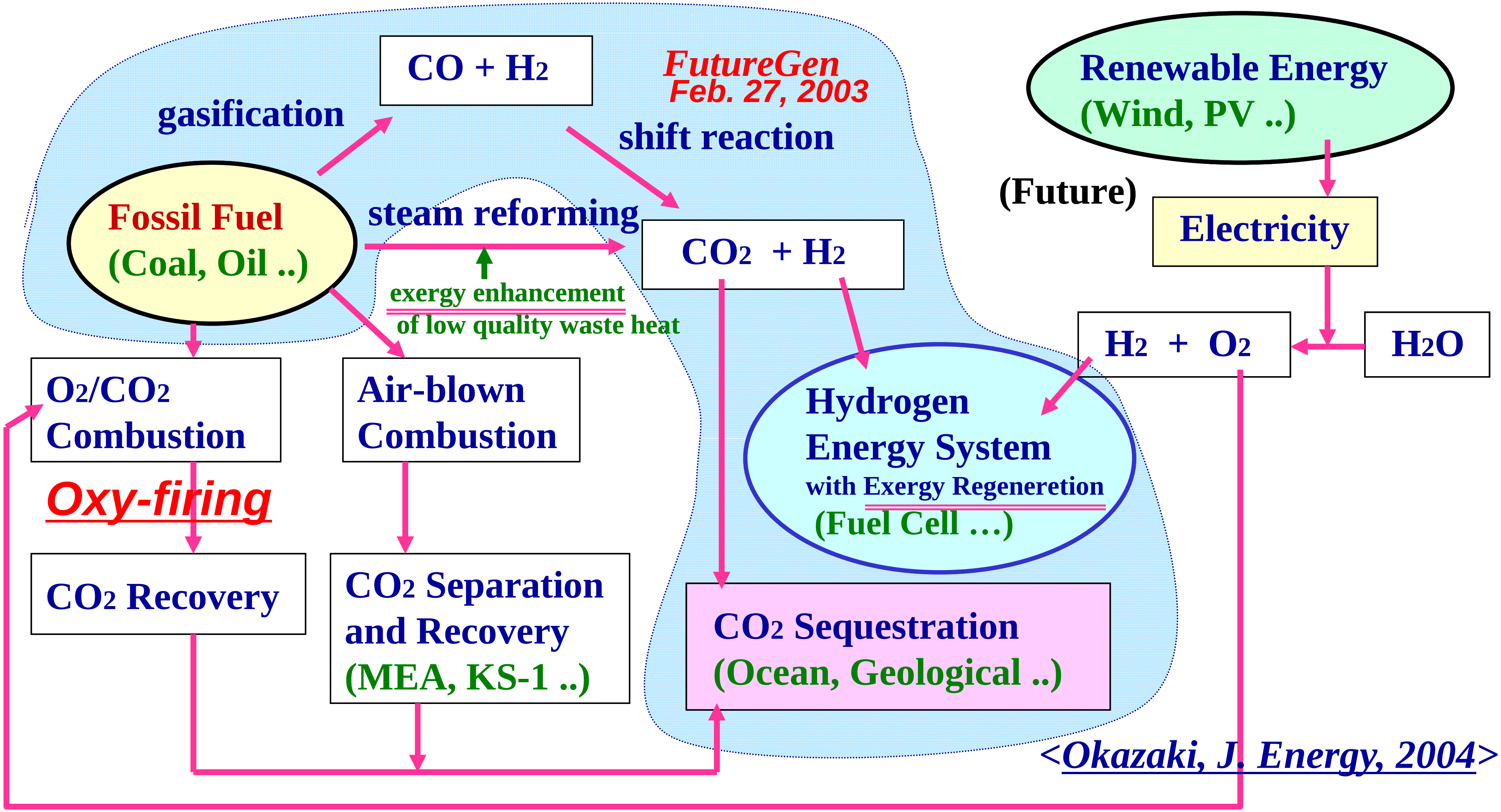
In Japan
1 GW P.C. Stations
Net eff. > 40 %
NOx < 100 ppm

Acid Rain
technology transfer from Japan

CO_2 Problems
only increase of eff. is not enough, and new strategies are definitely necessary.

No.1 Isogo Power Station of J-POWER (600 MW)

World Trend of CO_2-free Clean Coal Technology



Integration of Coal, Hydrogen and CO_2 Sequestration

O_2/CO_2 (Oxy-firing) Coal Combustion

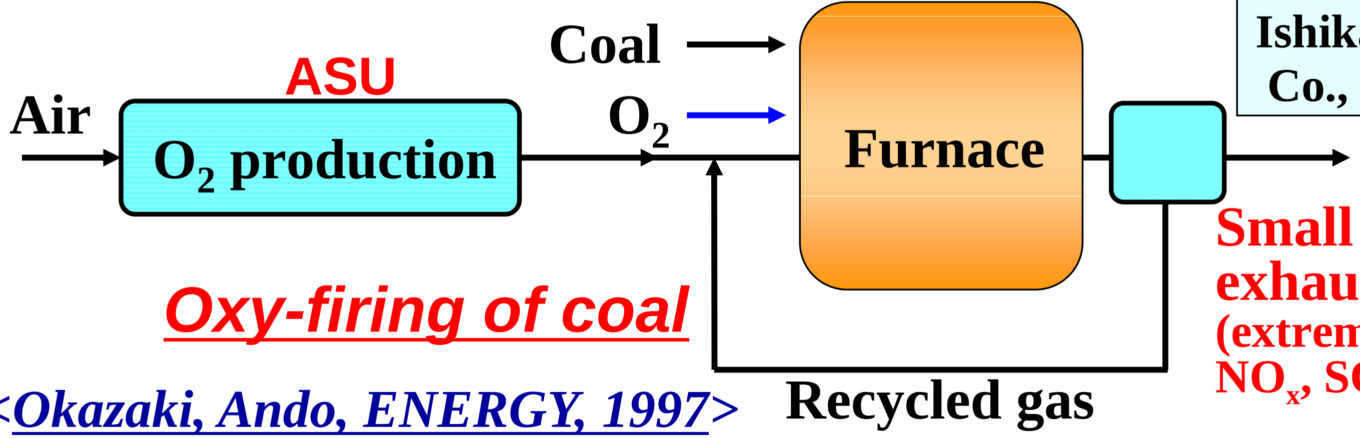
Conventional pulverized coal combustion

CO_2 concentration in flue gas is about 13 % → Great energy consumption to separate CO_2

O_2/CO_2 pulverized coal combustion

CO_2 concentration in flue gas is enriched up to 95 % → Easy and efficient CO_2 recovery

Practically realized by Ishikawajimaharima Co., Ltd.



Small amount of exhausted gas (extremely low amount of NO_x, SO_x)

Oxy-firing of coal

<*Okazaki, Ando, ENERGY, 1997*>

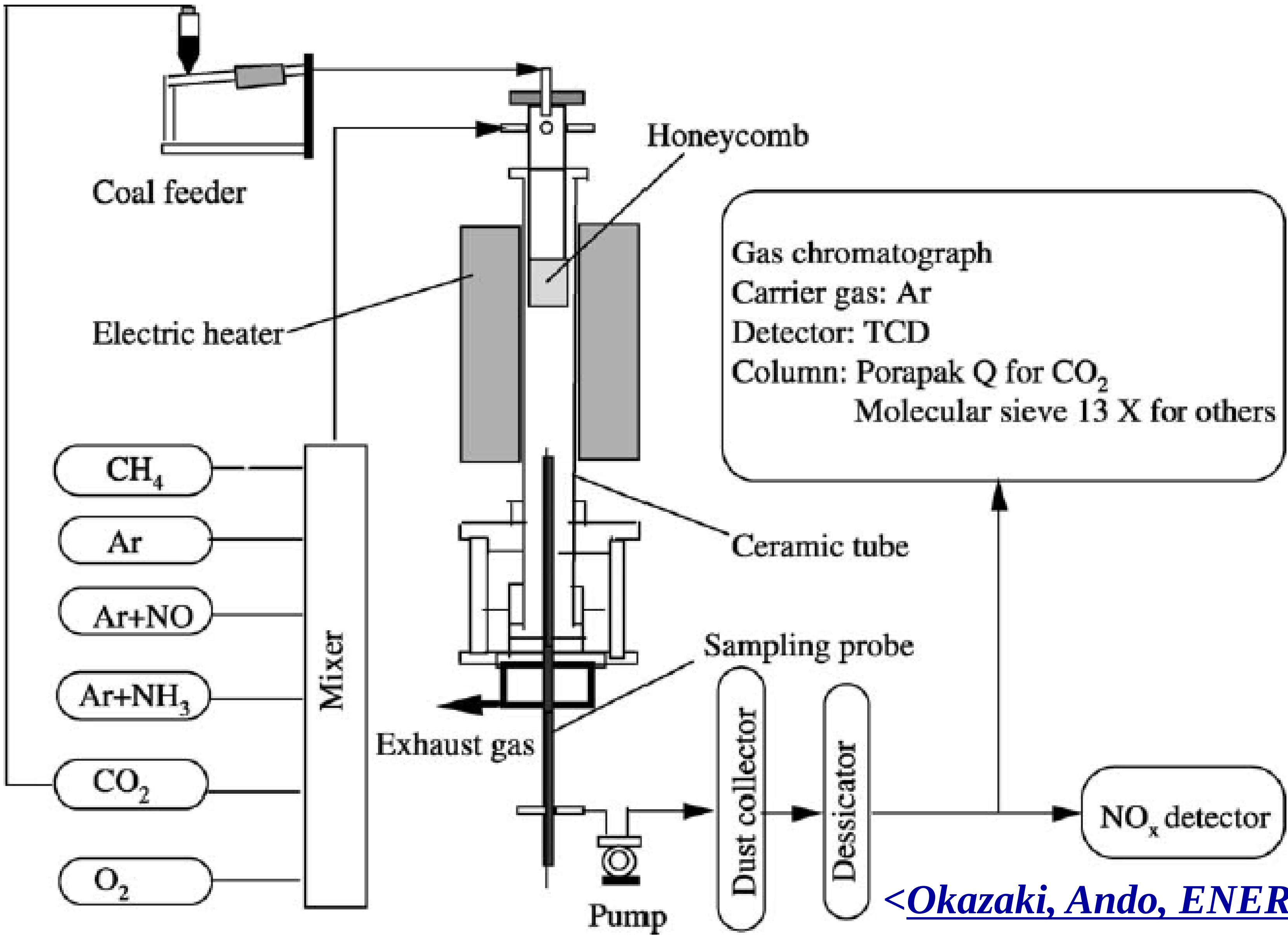
Needed Sub-Models for Oxy-PC Furnace

- Heat transfer sub-model
  - Radiant zone
  - Convection zone
- Coal jet ignition sub-model
  - Chemistry
  - Burner aerodynamics and heat transfer
- Char burnout sub-model
- Ash partitioning sub-model
  - Deposition
  - Trace metals
- Combustion by-products
  - NO_x, SO_x, Hg
- Integrated furnace model

TIT - HUST

Trace element behavior *(JST-NSFC)*

<J.O.L. Wendt, 2007 AIChE Meeting>



<*Okazaki, Ando, ENERGY, 1997*>

Experimental system to simulate O_2/CO_2 coal combustion

Drastic NOx Reduction (NOx: mainly due to Fuel-NOx)

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

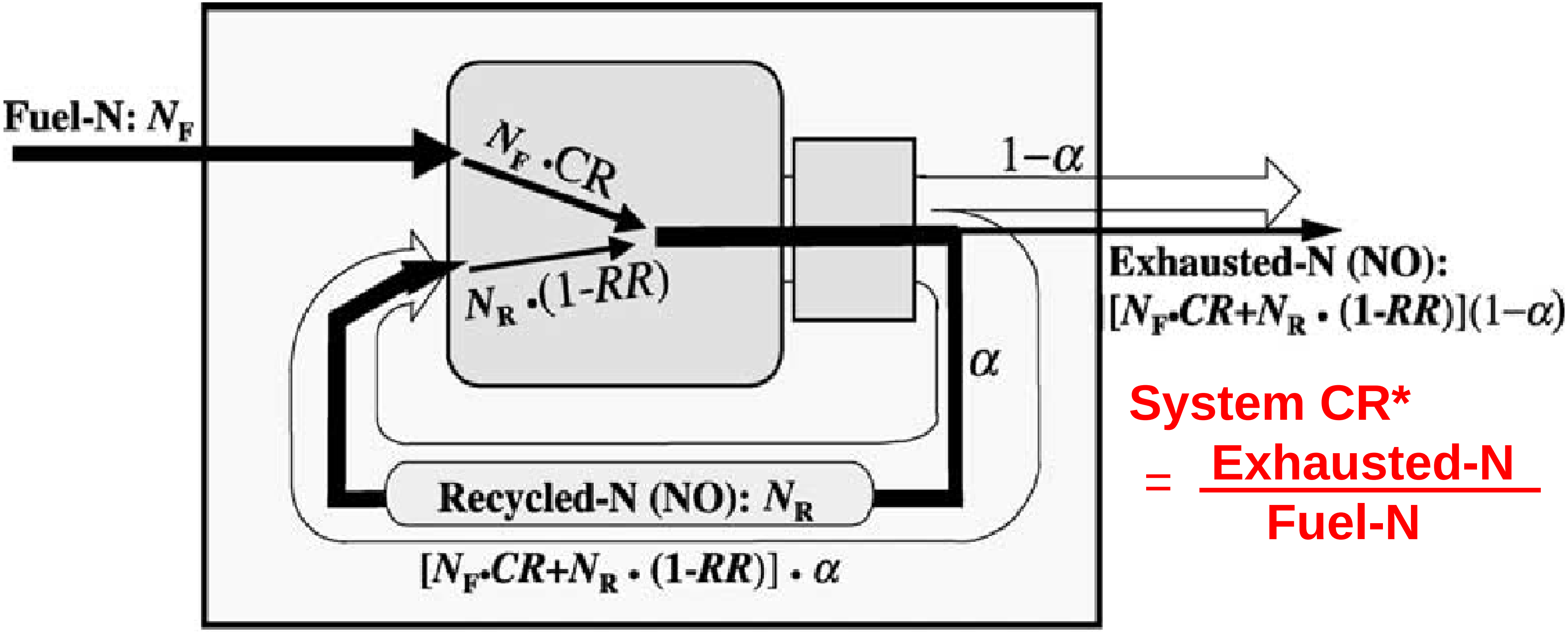
Summary of CR^* values for O_2/CO_2 coal combustion

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

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

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

Mass balance of N-atoms



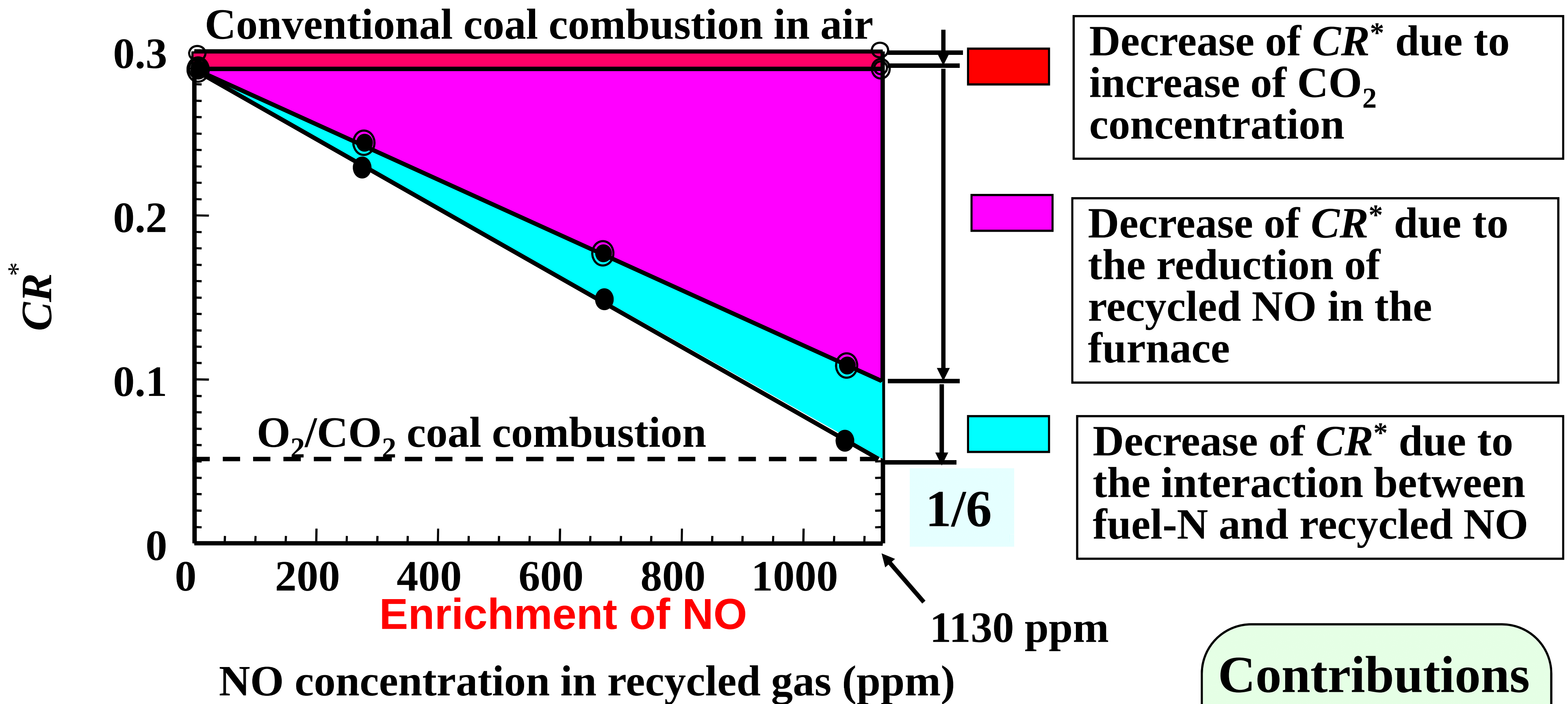
System CR*

$$= \frac{\text{Exhausted-N}}{\text{Fuel-N}}$$

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

local CR and local RR were experimentally identified.

<Okazaki, Ando, ENERGY, 1997>



Contributions

red	4 %
magenta	78 %
cyan	18 %

T_{max} = 1450 K Fuel-N = 1.22 wt % (as N atom mass)

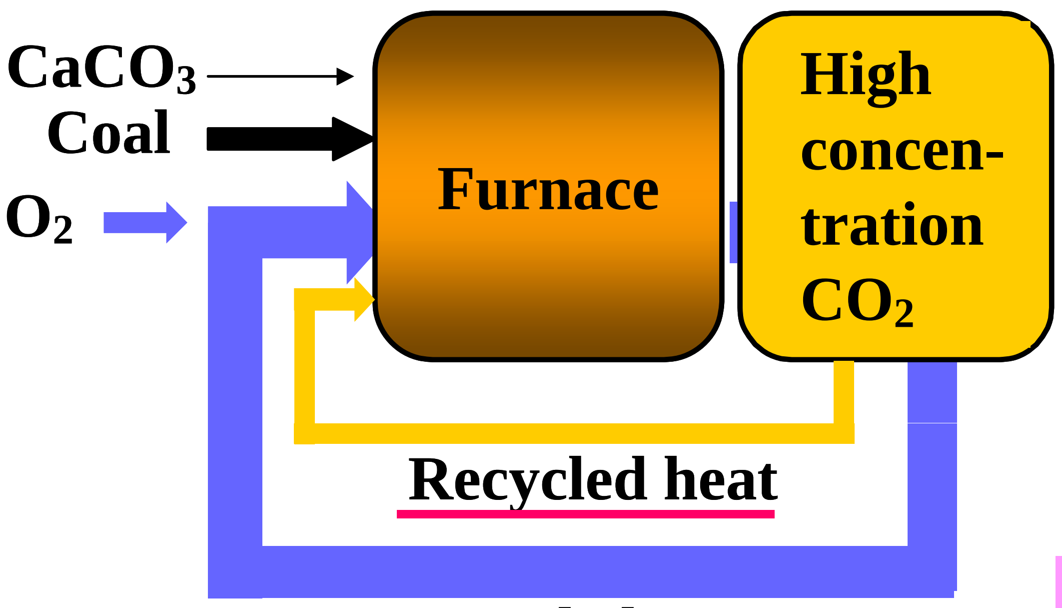
β = 0.2 $CO_2/(CO_2+Ar)$ = 0.48 (vol.) λ = 0.7

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

<*Okazaki, Ando, ENERGY, 1997*>

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

Further NOx Reduction by Heat Recirculation



Recycled gas

(Mainly CO_2 including NOx, SOx)

Easy and efficient CO_2 separation · recovery

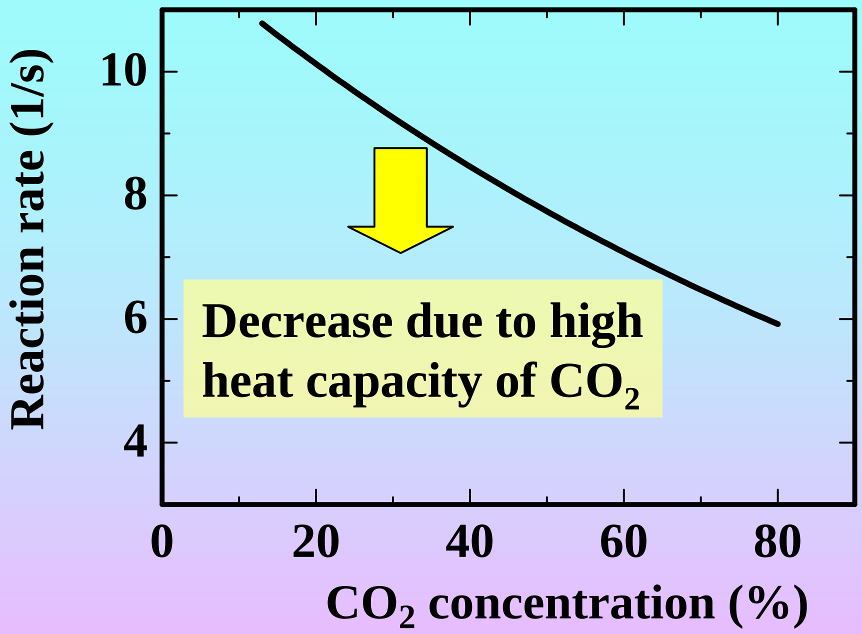
<*Liu & Okazaki, FUEL, 2003*>

Small amount of exhausted flue gas (Extremely low NOx, SOx emissions)

Schematic of O_2/CO_2 Coal Combustion with both mass and heat recirculation

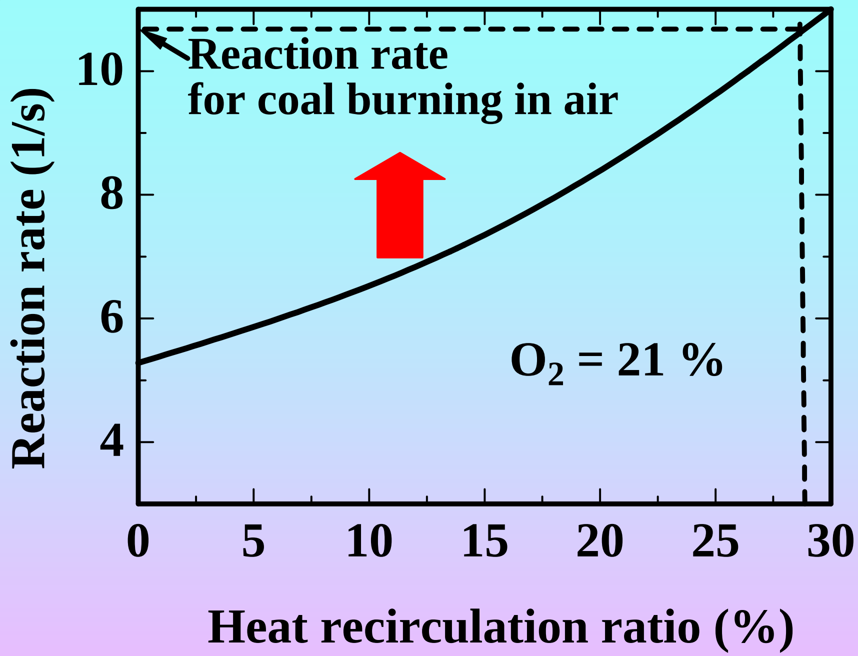
Additional merits

- Intensify coal combustion
- Decrease NO further through combustion with low O_2 concentration
- Improve fuel flexibility
- Broaden load change range of a boiler



O_2 = 21 vol. % $r = 3.125\times10^{-5}$ m

Reaction rate of coal burning versus CO_2 concentration

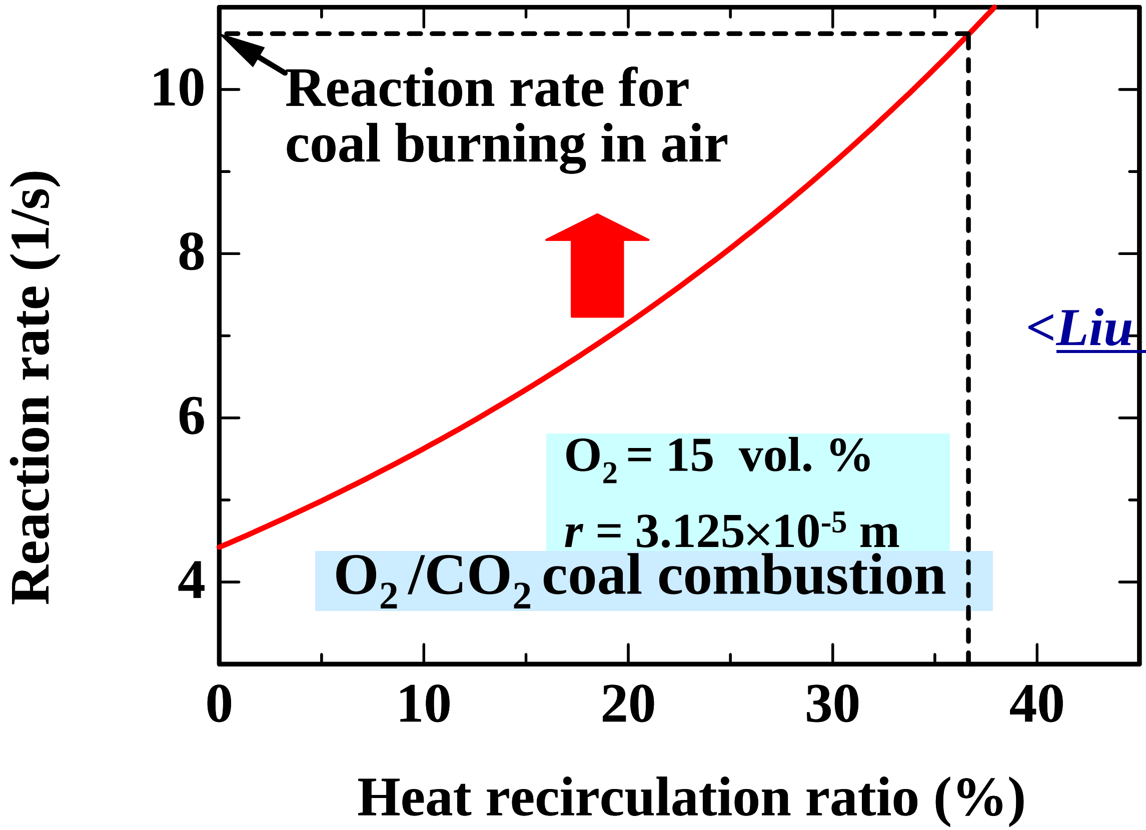


O_2 = 21 vol. % $r = 3.125\times10^{-5}$ m

O_2/CO_2 coal combustion

Effect of heat recirculation on reaction rate of coal burning

Heat recirculation ratio = (heat recycled)/(heating value of coal)



<*Liu & Okazaki, FUEL, 2003*>

Decrease NO further

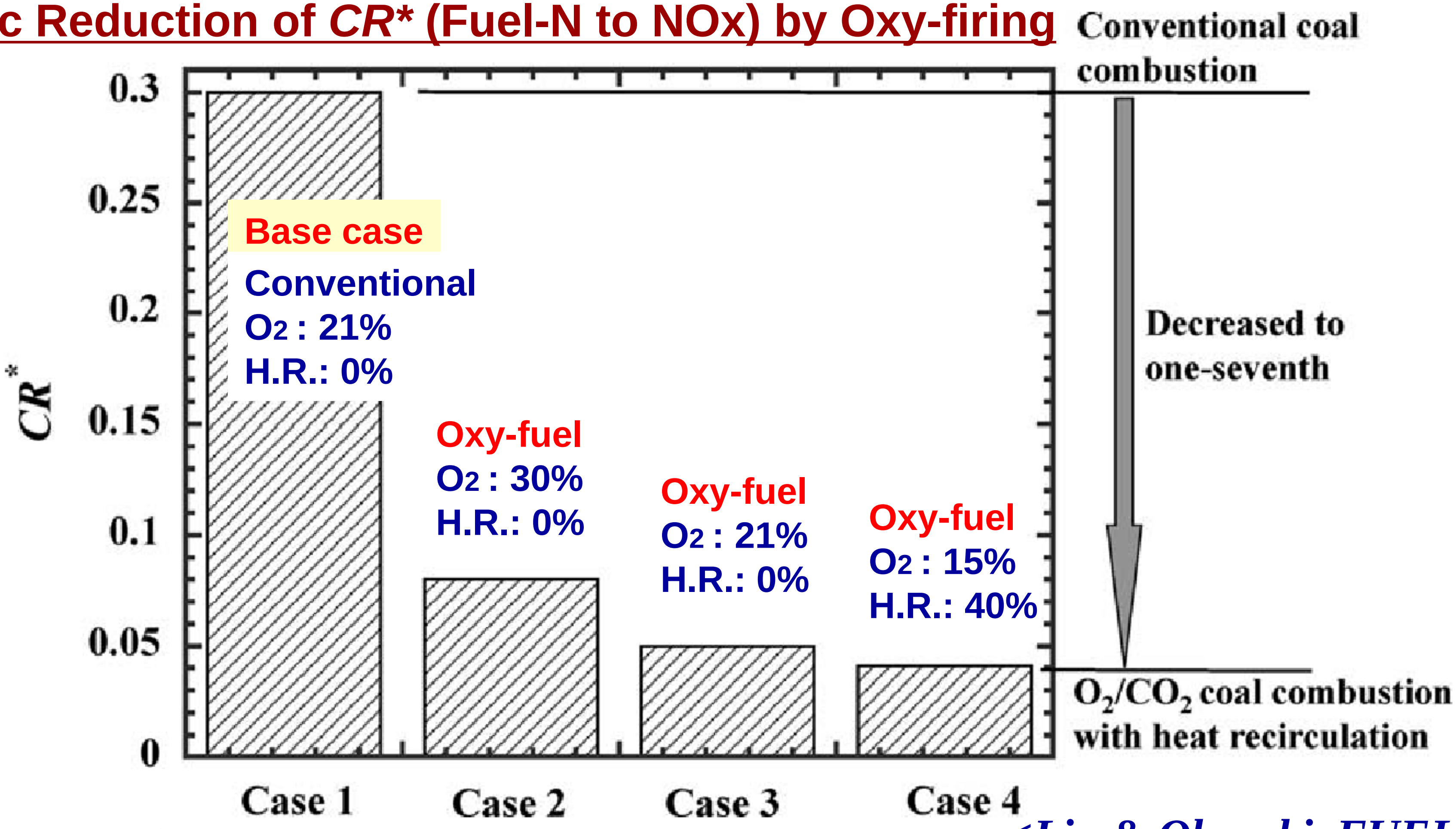
37 % of heat recirculation can compensate the decrease of coal burning caused by

a low O_2 concentration of 15 vol. %

high heat capacity of CO_2

Effect of heat recirculation on reaction rate of coal burning

Drastic Reduction of *CR** (Fuel-N to NOx) by Oxy-firing

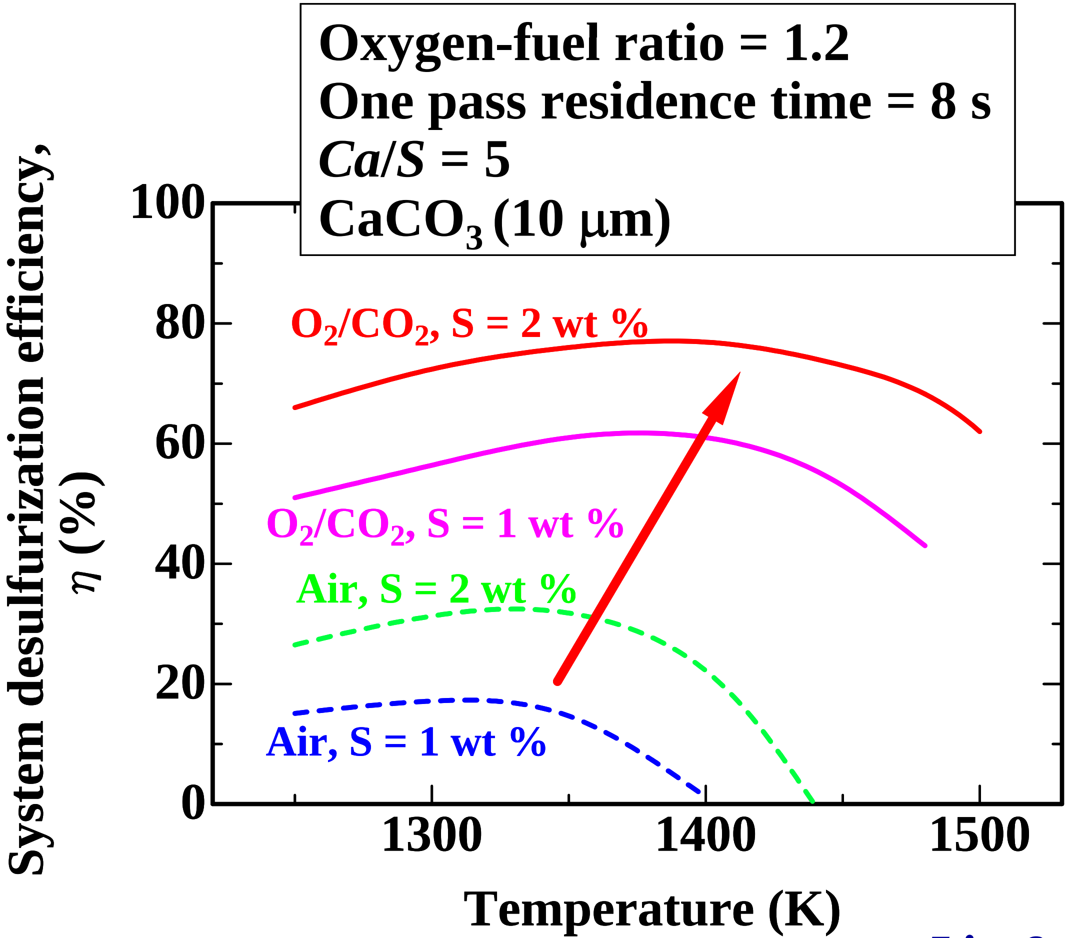


<Liu & Okazaki, FUEL, 2003>

Various cases for CR* estimation

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

Drastic Enhancement of In-furnace Desulfurization Efficiency



η at S = 1 wt %

six times higher

In-furnace desulfurizatioin at high temperature

Air: impossible

O_2/CO_2: can be realized

<*Liu & Okazaki, EERGY & FUEL, 2001*>

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

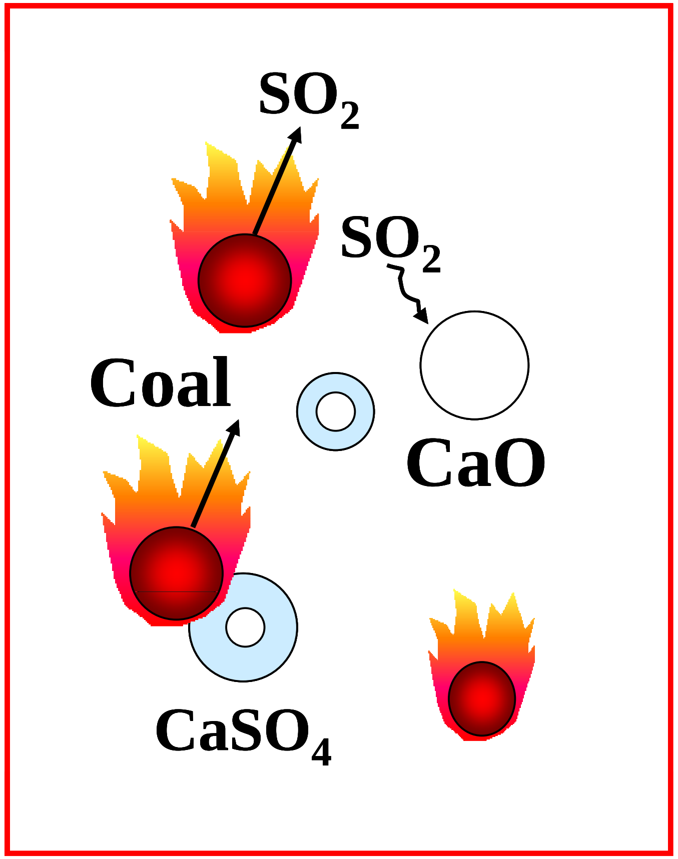
Effect of temperature on system desulfurization efficiency

Mechanism of In-furnace Desulfurization

What is in-furnace desulfurization?

A very economical method of SO_2 removal through sorbent ($CaCO_3$) injection into the furnace

<Liu & Okazaki, EERGY & FUEL, 2001>



Desulfurization reaction:

$$CaCO_3 \rightarrow CaO + CO_2$$

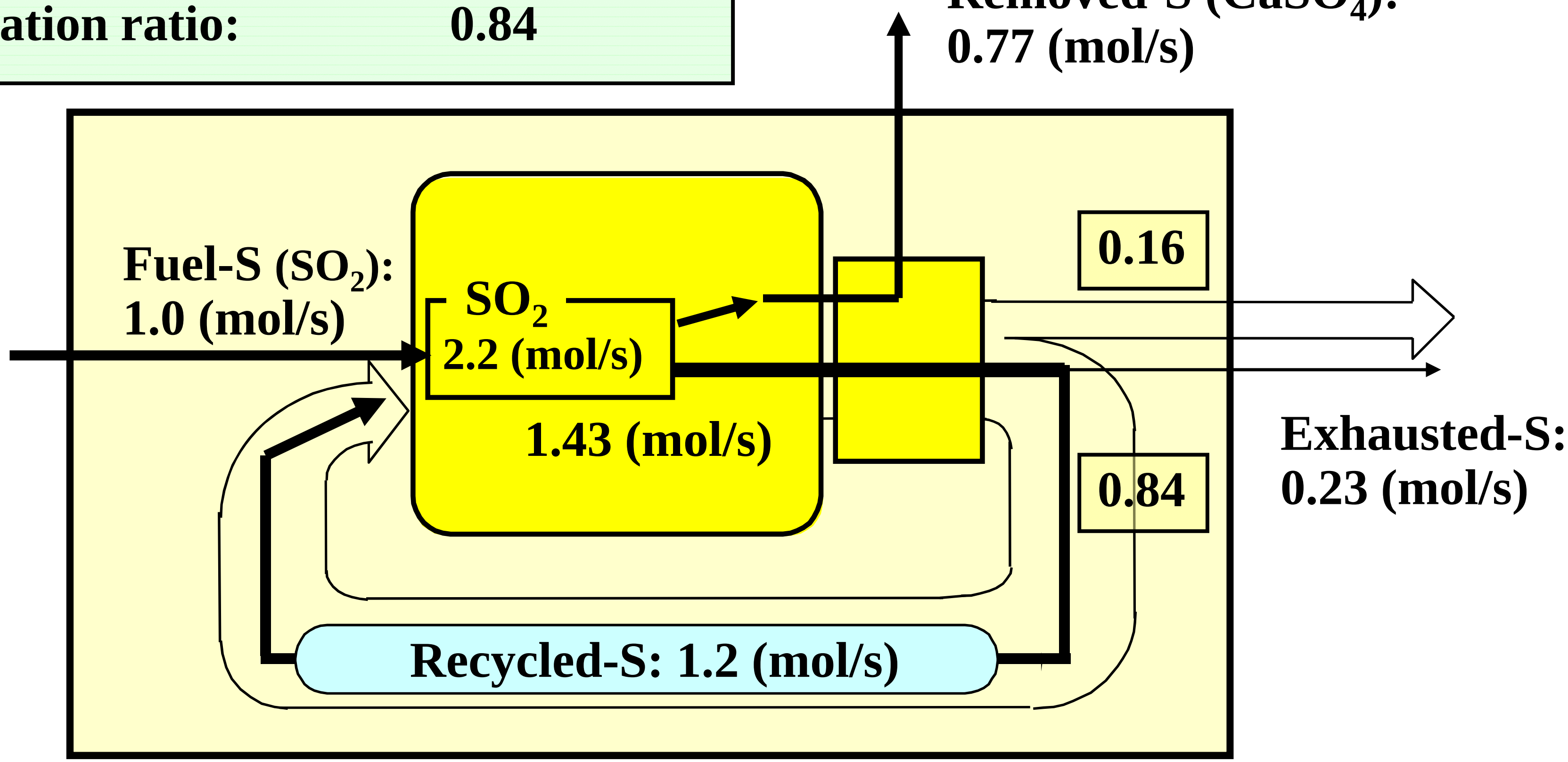
$$CaO + SO_2 + 1/2O_2 \rightarrow CaSO_4$$

$CaSO_4$ decomposition:

$$CaSO_4 \rightarrow CaO + SO_2 + 1/2O_2$$

The cause of decrease in desulfurization efficiency at high temperature

Local desulfurization efficiency 0.35
Gas recirculation ratio: 0.84



System desulfurization efficiency: η = 77 %

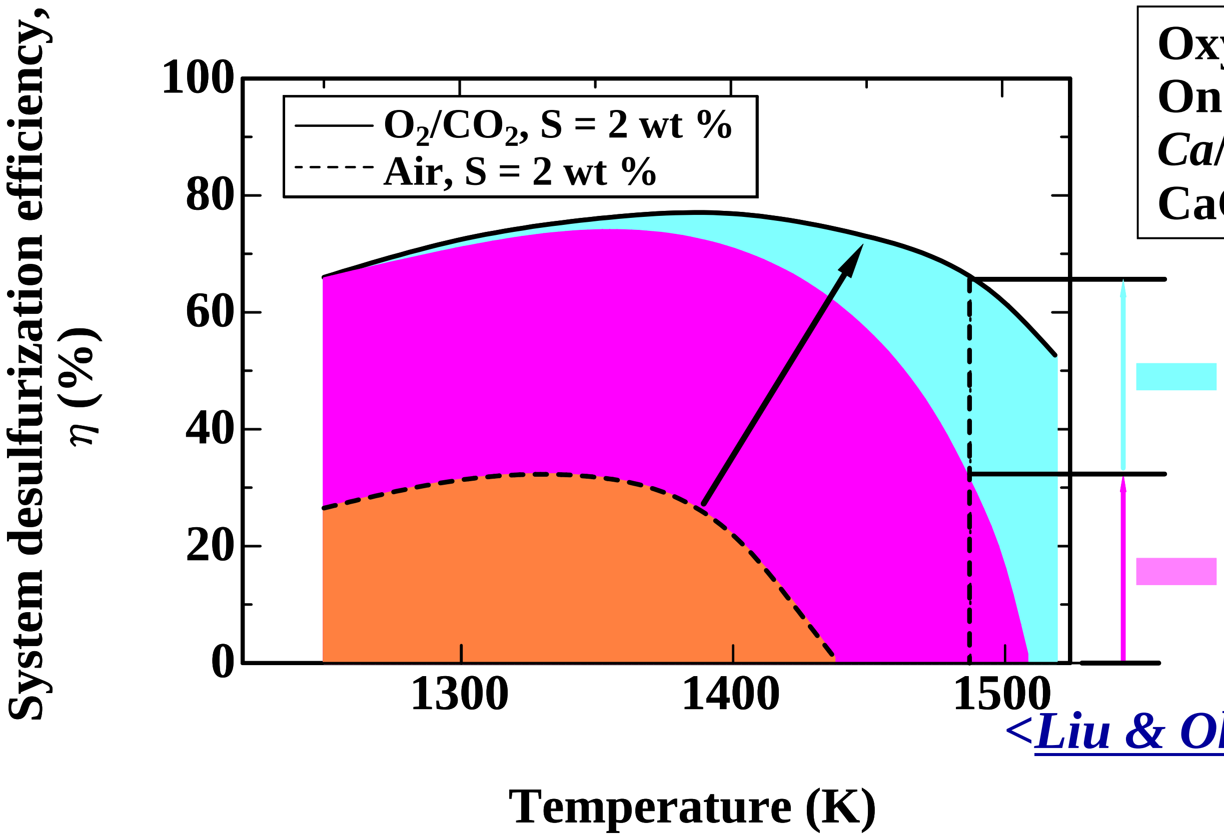
<*Liu & Okazaki, EERGY & FUEL, 2001*>

Coal property (wt. %, dry)

C: 71.1 O: 8.86
H: 4.23 N: 1.76
S: 2.00

Calculation conditions

Oxygen-fuel ratio = 1.2, Temperature = 1400 K
one pass residence time = 8 s, *Ca/S* = 5, $CaCO_3$ (10 μm)



Oxygen-fuel ratio = 1.2
One pass residence time = 8 s
Ca/*S* = 5
$CaCO_3$ (10 μm)

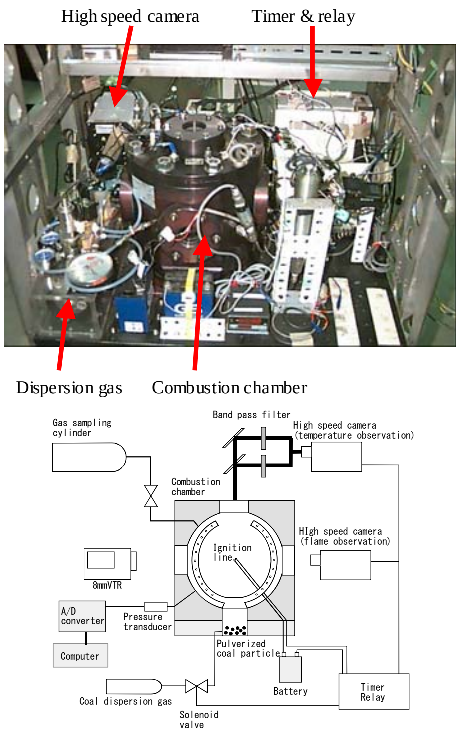
<*Liu & Okazaki, EERGY & FUEL, 2001*>

Increase of η due to inhibition of $CaSO_4$ decomposition — Contributes over 2/3 above 1500 K

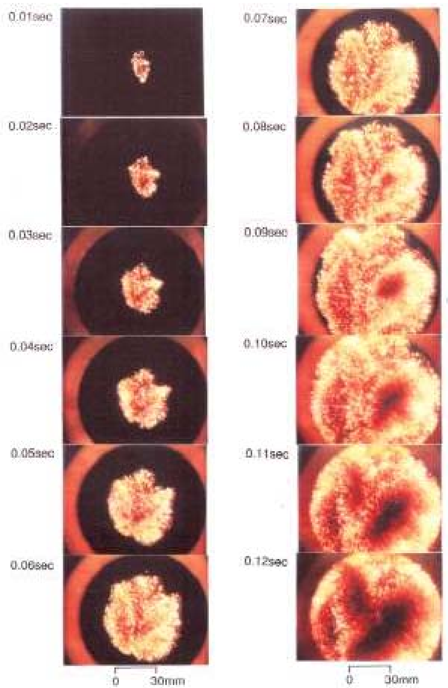
Increase of η due to recirculation of flue gas — Contributes over 2/3 below 1450 K

Contributions of different factors to the increase in system desulfurization efficiency

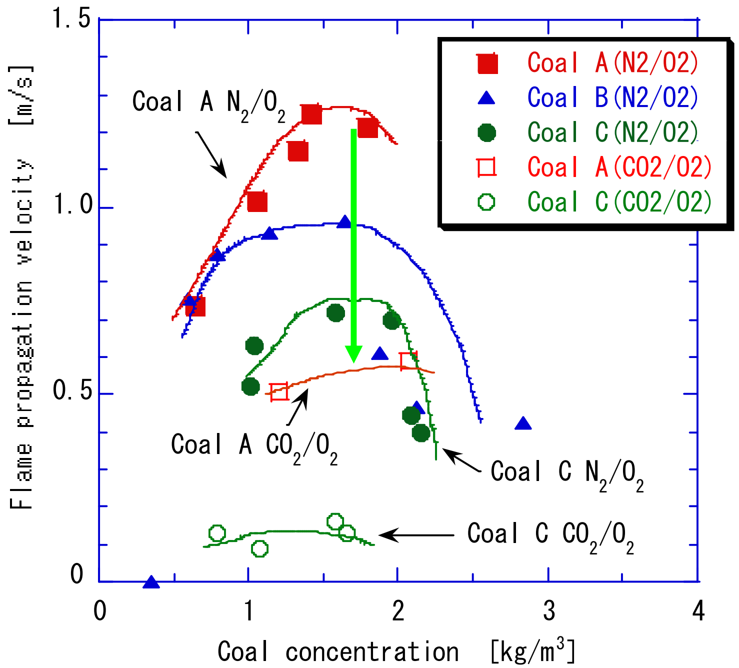
Flame Propagation Velocity in High CO_2 Concentration



Experimental Set-up



Flame Behavior

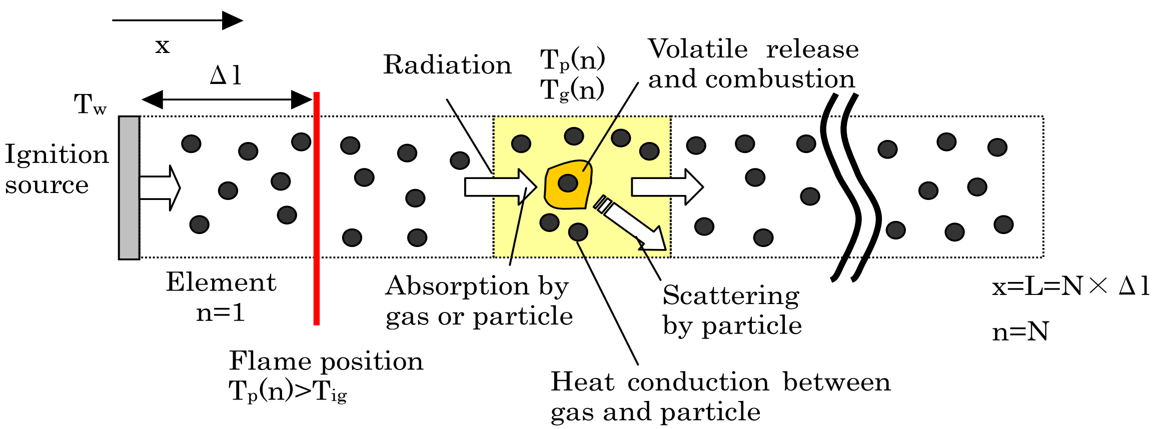


Flame Propagation Velocity

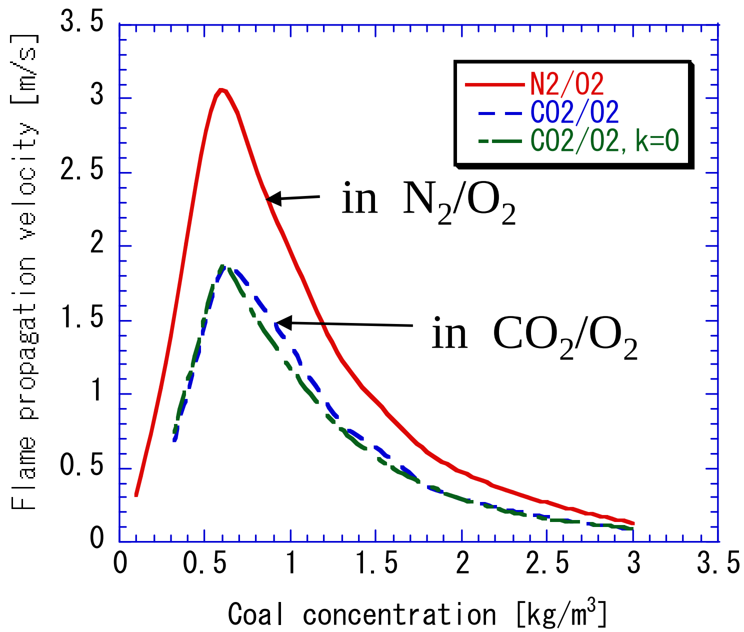
Flame propagation velocity in CO_2/O_2 largely decreases to 1/3 – 1/5 of that in N_2/O_2

<*Suda & Okazaki, FUEL, 2007*>

One-Dimensional Flame Propagation Model



One-Dimensional Model

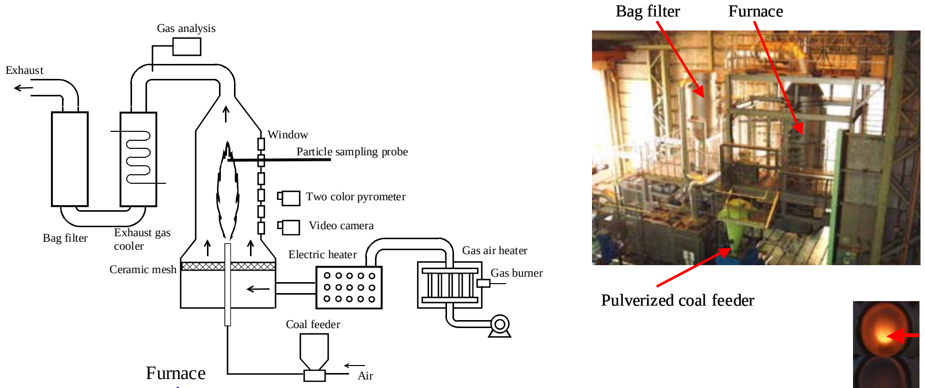


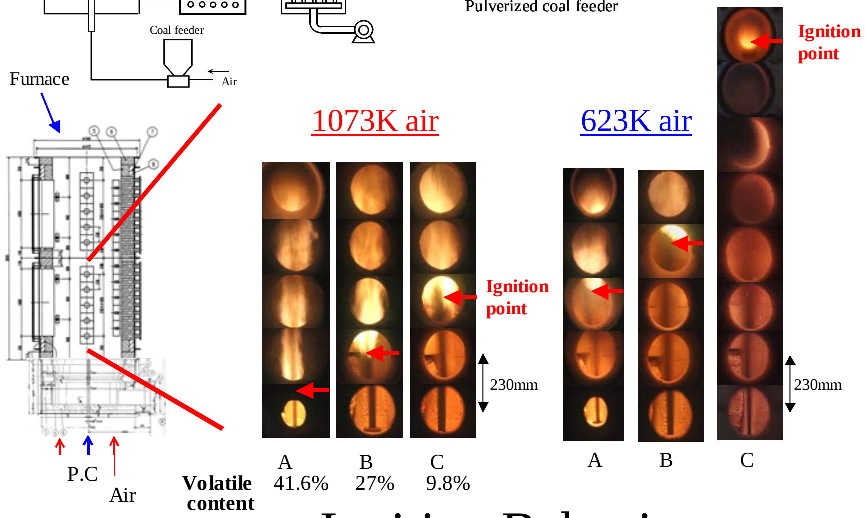
Calculated Results of Flame Propagation Velocity

Large decrease of flame propagation velocity is mainly due to large heat capacity and small thermal diffusivity in CO_2/O_2

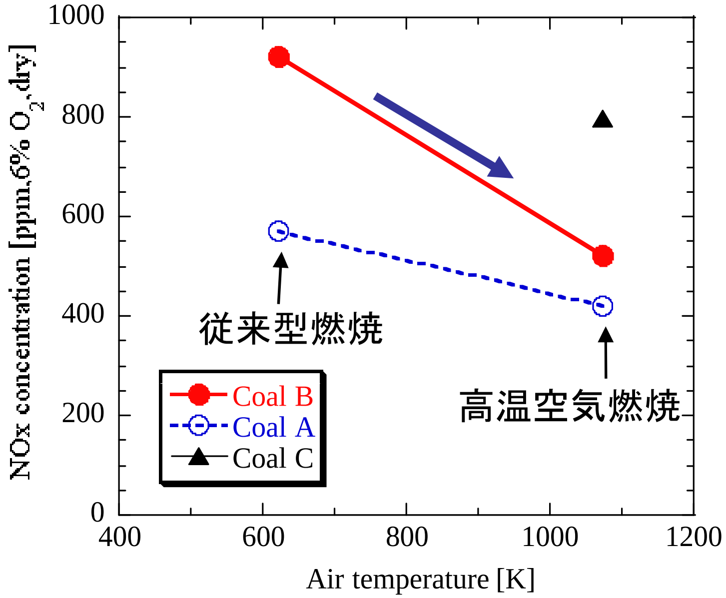
<***Suda & Okazaki, FUEL, 2007***>

Flame Stabilization and Further Low-NOx by High Temperature Air Combustion





Ignition Behavior



NOx Reduction by Higher Air Temperature

Flame stabilization by high temperature air combustion

Further low-NOx by stronger reducing condition near a burner

Australia/Japan Oxy-firing Project

JCOAL Japan Coal Energy Center · IHI

Scheme

Australia

- Coal 21
  - Project manager
    - Electric companies
    - Coal suppliers
    - Research Gr.

cs energy generations ahead

Japan

NEDO: New Energy and Industrial Technology Development Organization

Advisory Group:

- *Tokyo Institute of Technology*
- National Institute of Advanced Industrial Science and Technology
- Electric Power Development Co.,Ltd.
- Central Research Institute of Electric Power Industry
- Nippon Sanso Corporation
- Research Institute of Innovate Technology for the Earth

JCOAL: Application study of Oxy-firing technology in other region

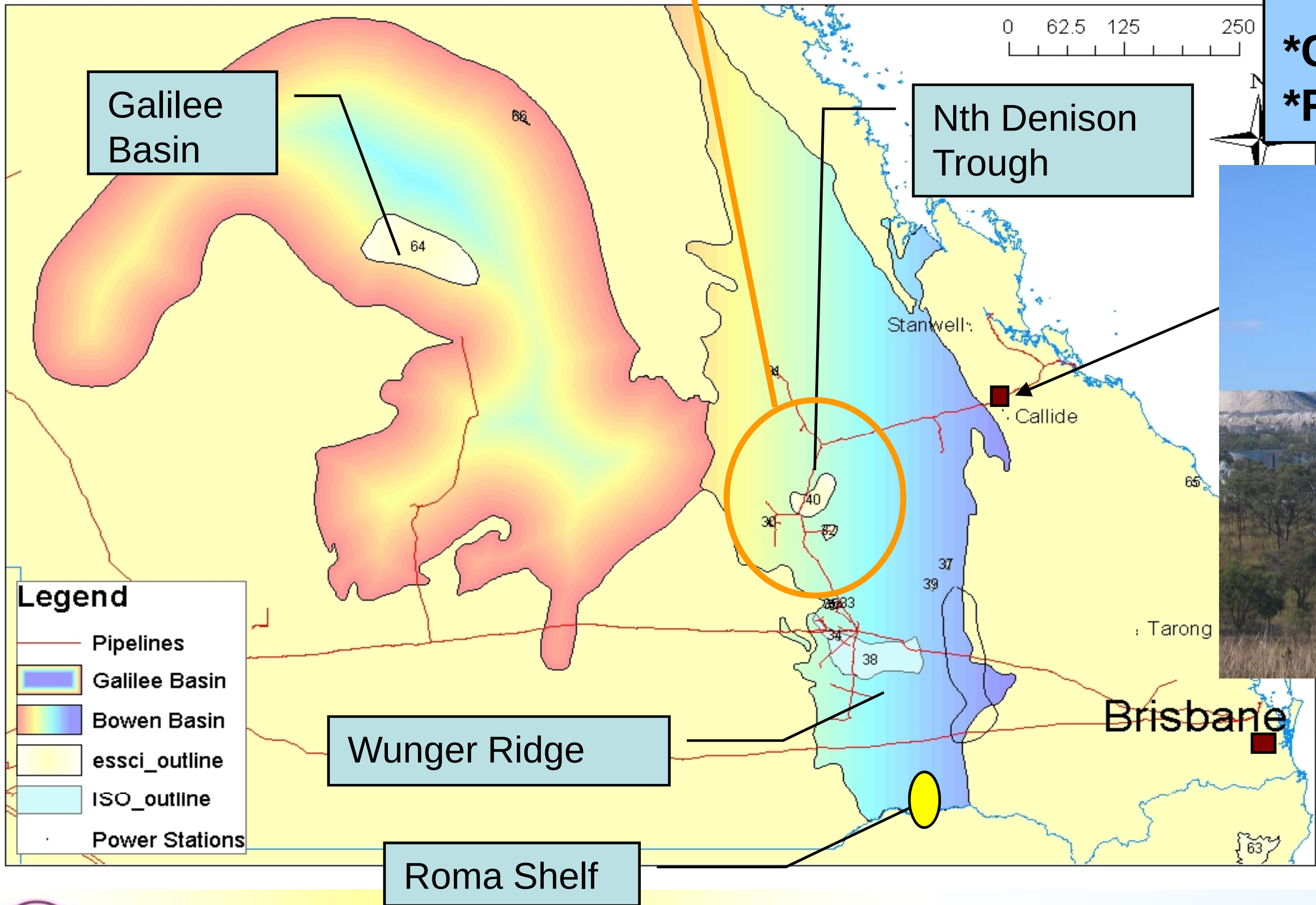
IHI: Study of boiler conversion to Oxy-firing

Australia/Japan Oxy-firing Project
Site of Power Station and Storage

JCOAL Japan Coal Energy Center | IHI | cs energy generations ahead

CO_2 storage site
*Type: Depleted gas reservoir
*Capacity: Approx. 13million t-CO_2
*Approx. 250km west of power station

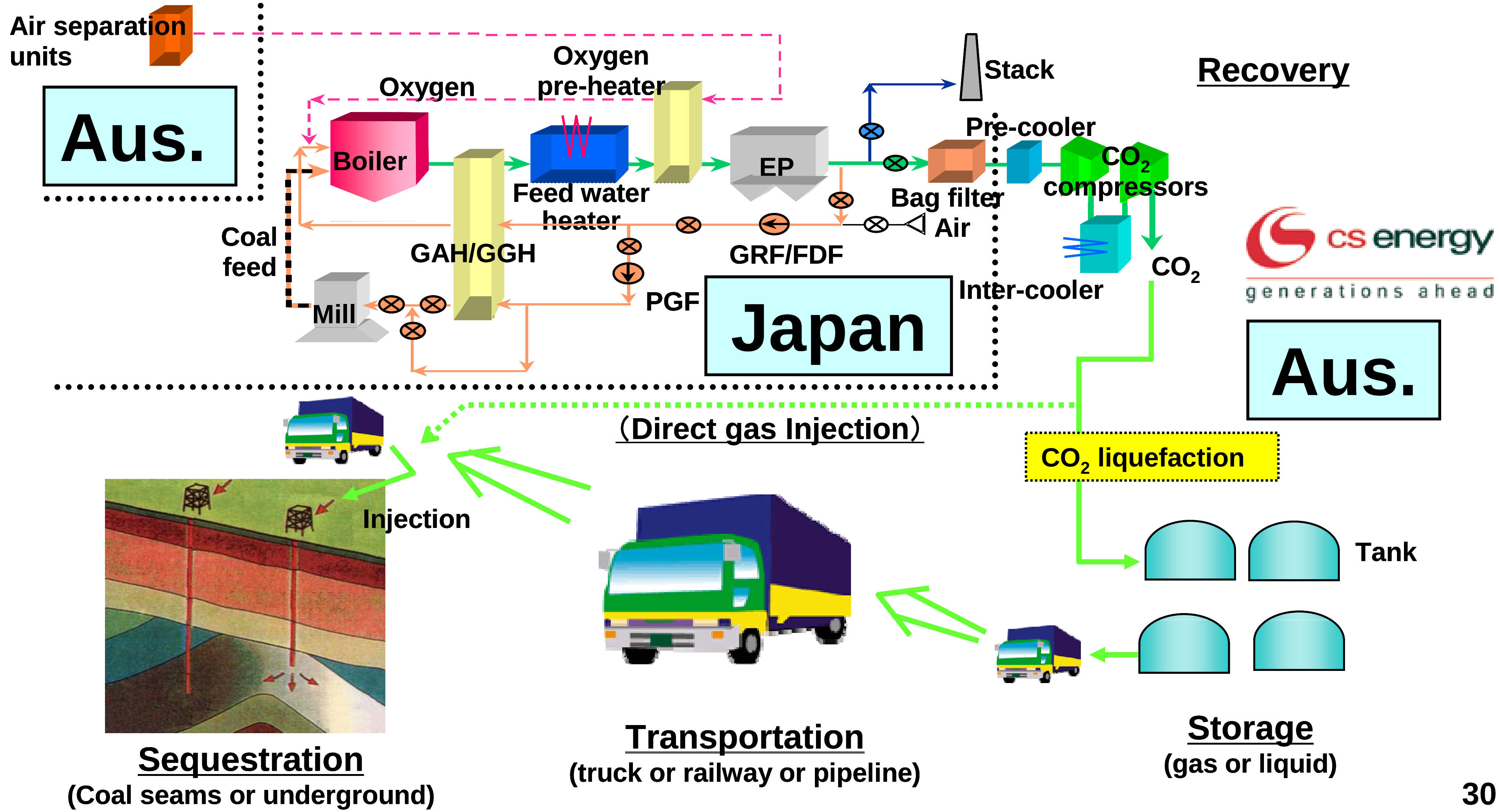
Power Plant
*Callide-A: 4 units x 30 MWe
*Evaporation:
123 t/h steam at 4.1 MPa, 460°C
*Commissioned: 1965 – 69
*Refurbished 1997/98



Callide-A PS

Australia/Japan Oxy-firing Project

JCOAL Japan Coal Energy Center IHI

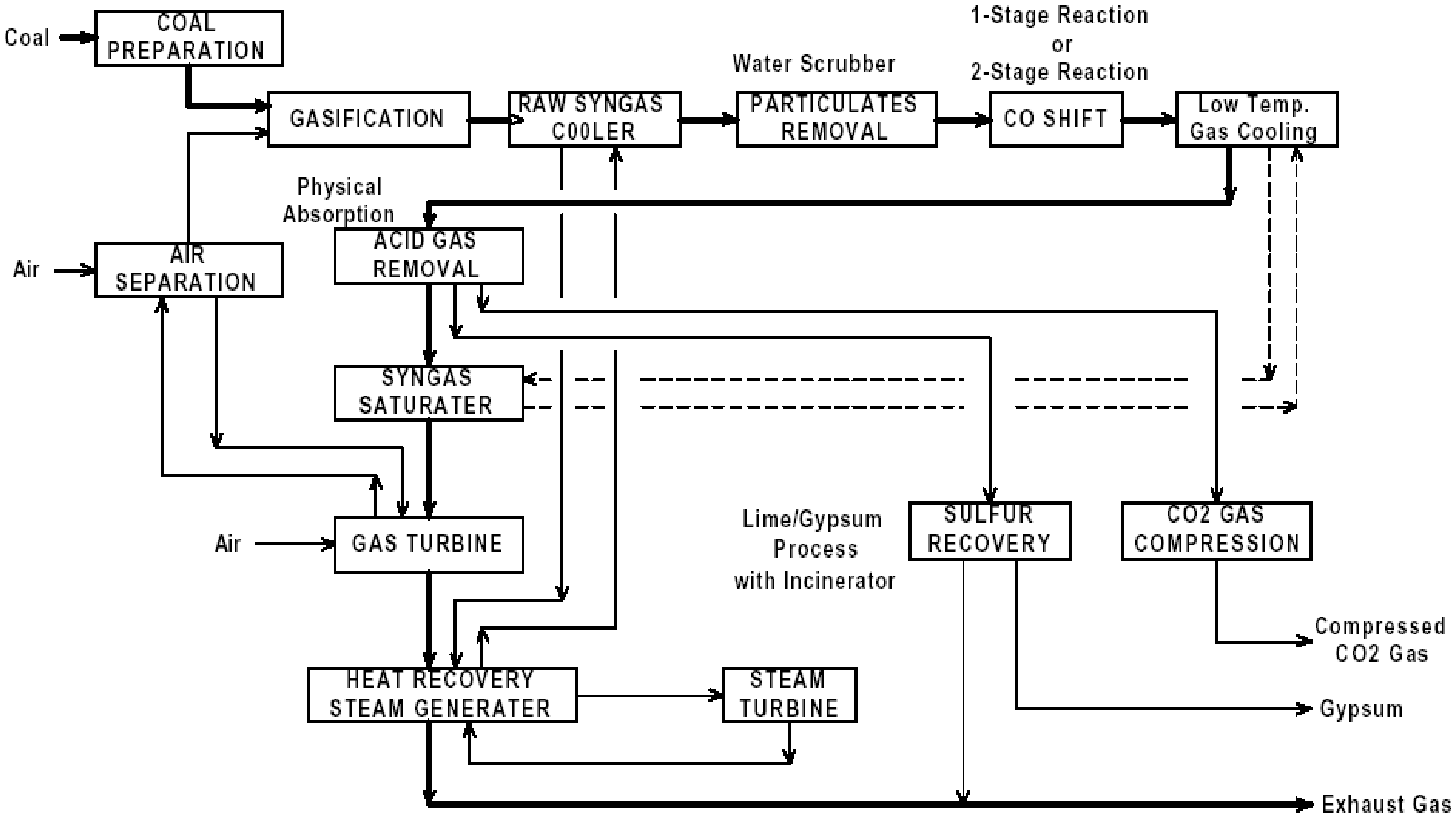


Net Energy Efficiency of Oxy-fired Coal Combustion

	Conventional combustion		O_2/CO_2
	Without CO_2 recovery	MEA*	
CO_2 recovery rate	-	90 %	90 %
Gross capacity	1000 MW	840 MW	1000 MW
Net capacity	946 MW	672 MW	720 MW
Gross efficiency	41.4 %	34.7 %	42.9 %
Net efficiency	39.1 %	27.8 %	30.9 %
O_2 production / CO_2 liquefaction	-	-	147 / 108 MW
CO_2 adsorption / CO_2 liquefaction	-	38 / 72 MW	-
Other utilities	54 MW	58 MW	25 MW

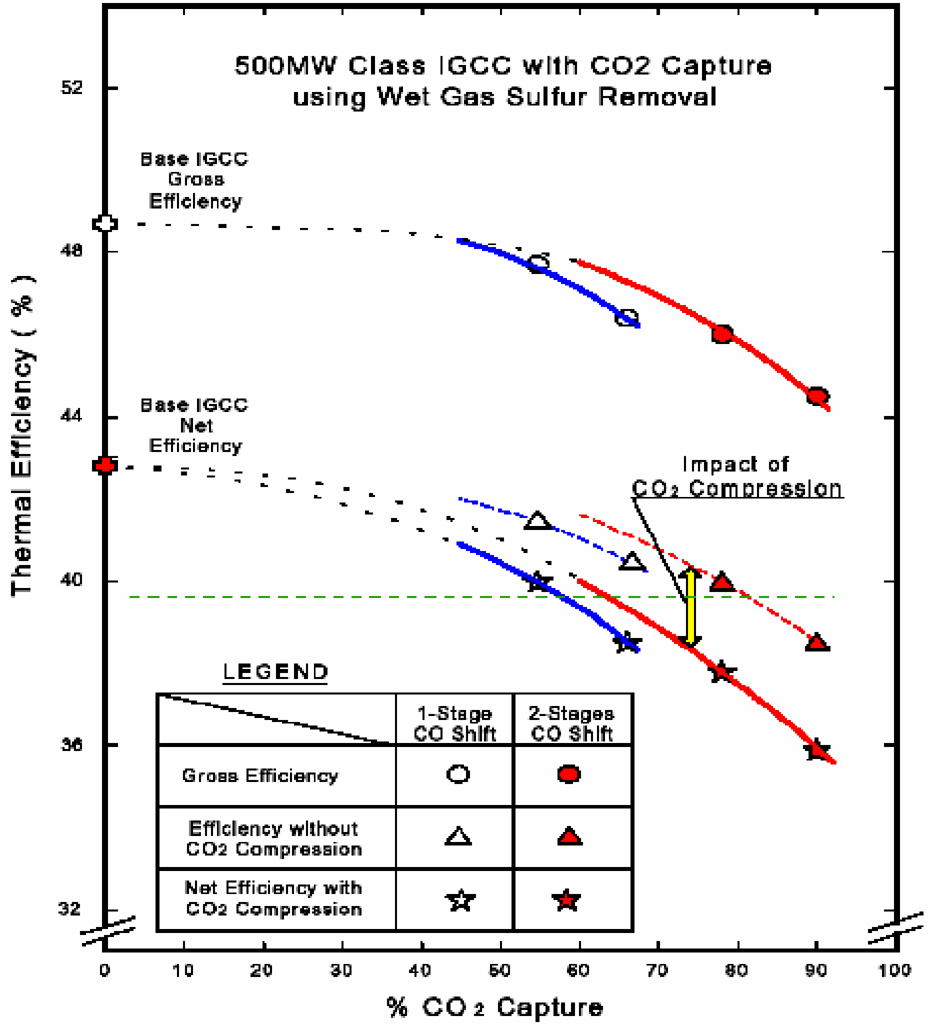
•MEA: Monoethanolamine, a typical absorbent used for CO_2 recovery in conventional coal combustion

Compensation of the decrease of net efficiency by combining active CO_2 recovery with IGCC



IGCC with CO2 Capture using Wet Gas Sulfur Removal

IGCC with Active CO_2 Recovery



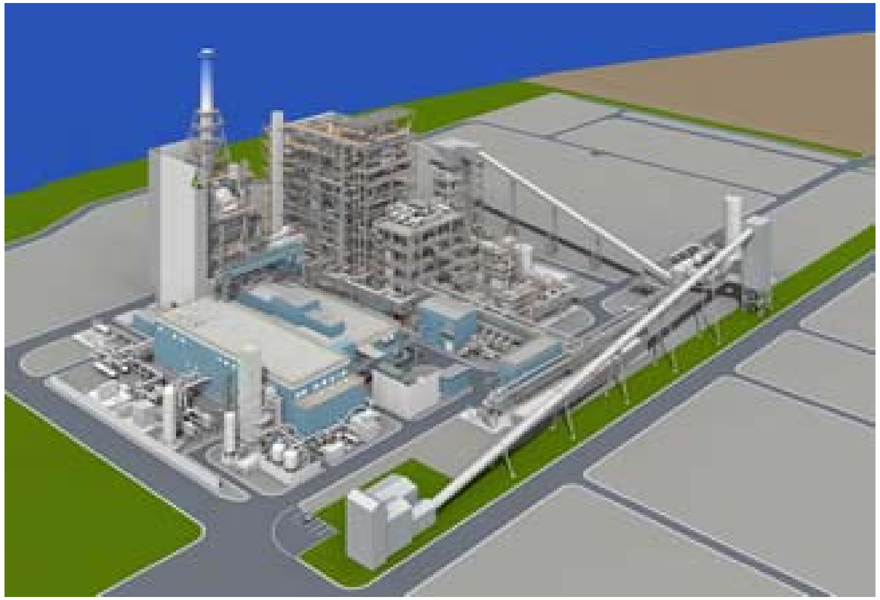
<Amaike, A-J TEC, 1999>

Net efficiency of IGCC with active CO_2 recovery

Integrated Coal Gasification Combined Cycle

IGCC (Integrated Coal Gasification Combined Cycle)

- Clean Coal Power R&D Co., Ltd.
- Air blown, entrained-flow gasifier
- 250MW demonstration, 2007-2009
- High efficiency (20% CO_2 reduction)



Bird eye's view of the demonstration plant

クリーンコールパワー研究所
Clean Coal Power R&D CO., LTD.

IGFC (Integrated Coal Gasification Fuel Cell Combined Cycle)

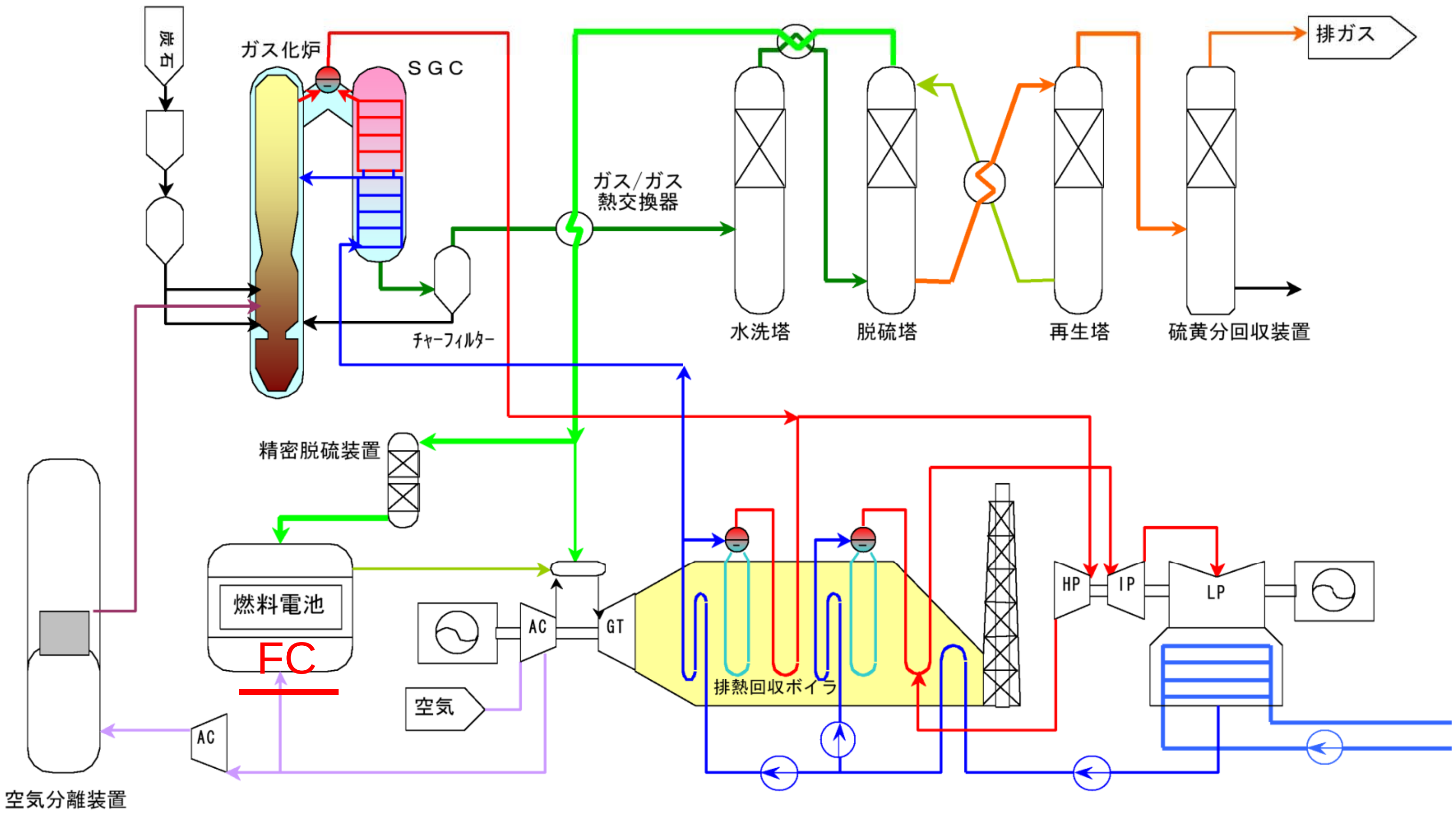
- **EAGLE** Project, J-Power (EPDC)
- Oxygen blown, entrained-flow gasifier
- 150t/d pilot test, 2001-2009
- High efficiency (30% CO_2 reduction)
- CO_2 capture test, 2007-

Coal Energy Application for Gas, Liquid & Electricity

Pilot plant at Wakamatsu Res. Inst., JPower

J-POWER 電源開発

IGFC



IGFC (Integrated Coal Gasification Fuel Cell Combined Cycle)

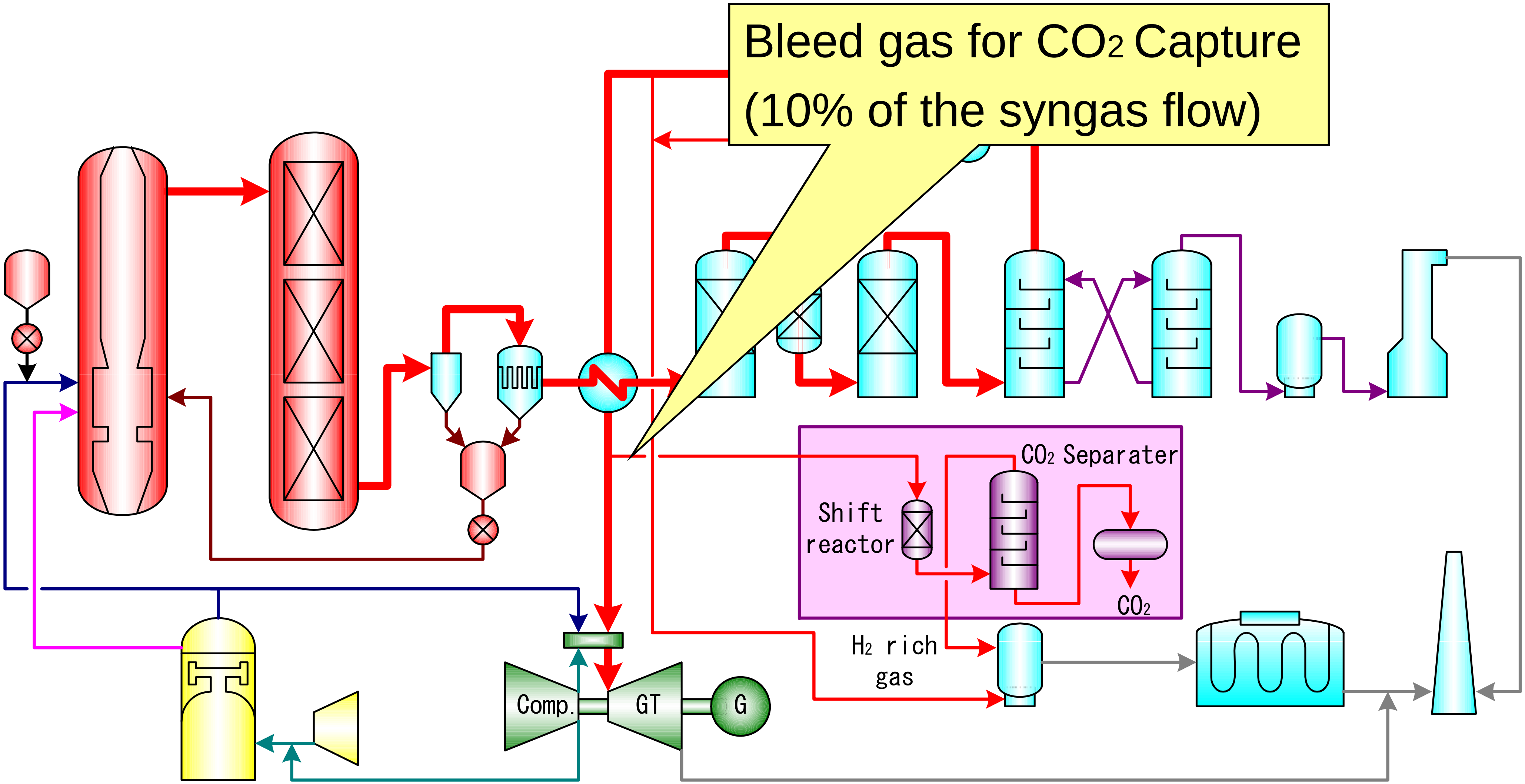
EAGLE (Coal Energy Application for Gas, Liquid & Electricity)

Schedule of the EAGLE Project (STEP-2)

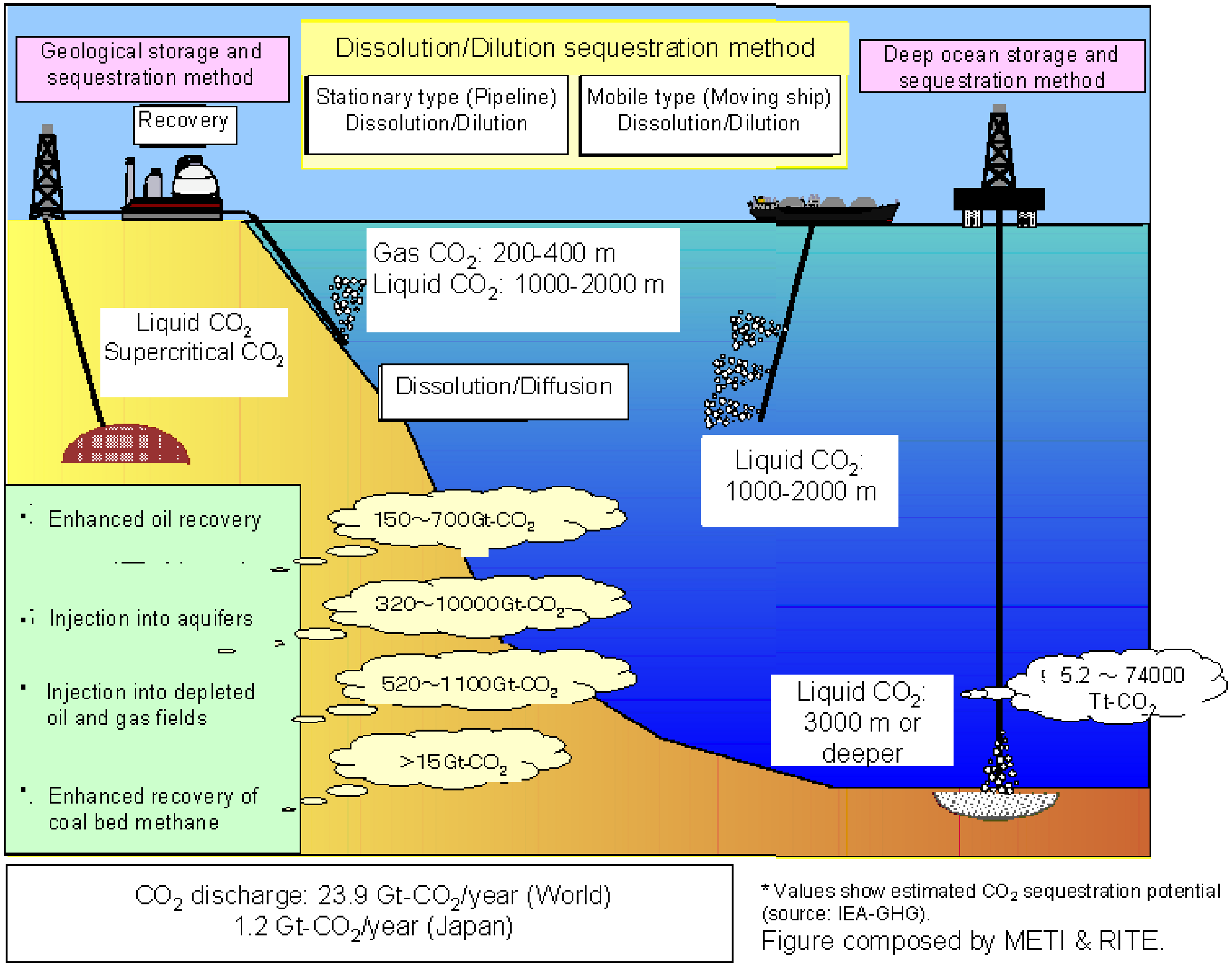
(FY)

	2007	2008	2009
CO_2 Capture	Design	Construction	Test
Coal flexibility test	Test	Remodeling Gasifier into high thermostability	Test
Survey of trace elements behavior	Test		Test

CO2 Capturing Test (without storage)



CO2 Sequestration Methodology

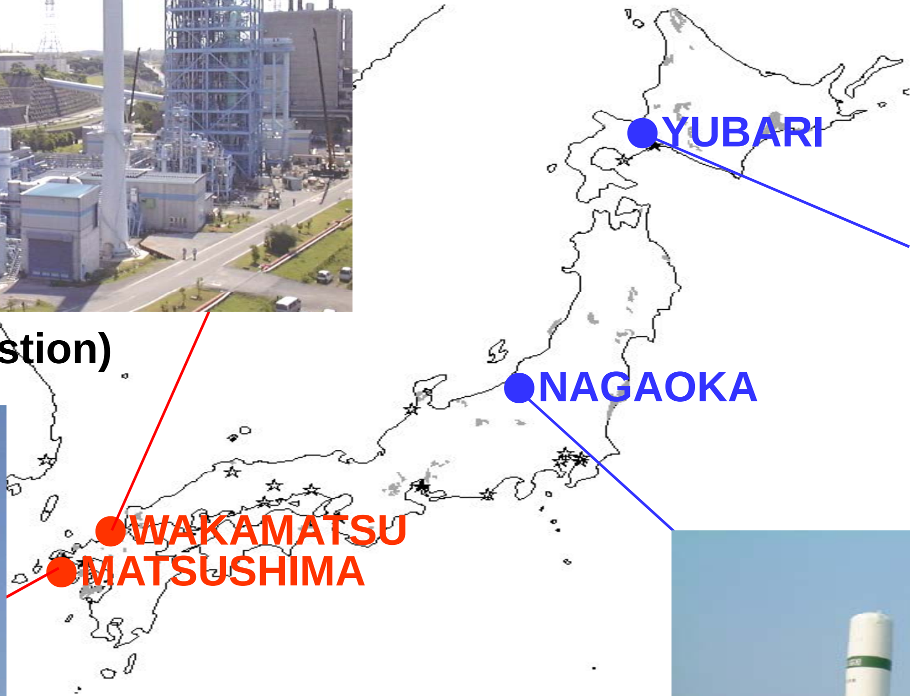


Sequestration technologies for a vast amount of CO_2

CCS field test sites in Japan

Source: NEDO Home page, RITE Home page, JCOAL Home page

Capture (pre-combustion)



Geosequestration (coal seam)

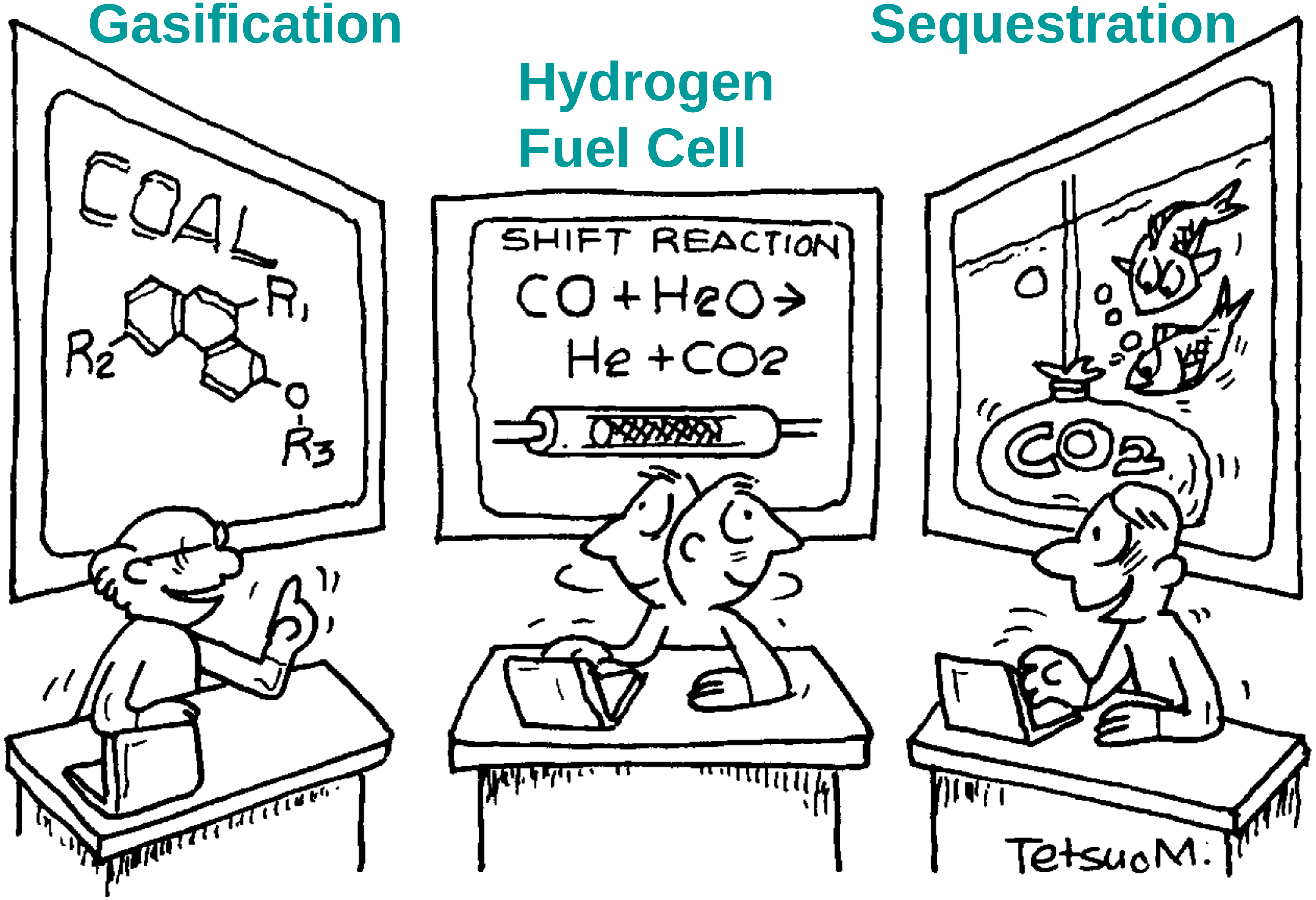
Capture (post-combustion)

Geosequestration (aquifer)

Coal
Combustion
Gasification

Hydrogen
Fuel Cell

CO_2
Recovery
Sequestration

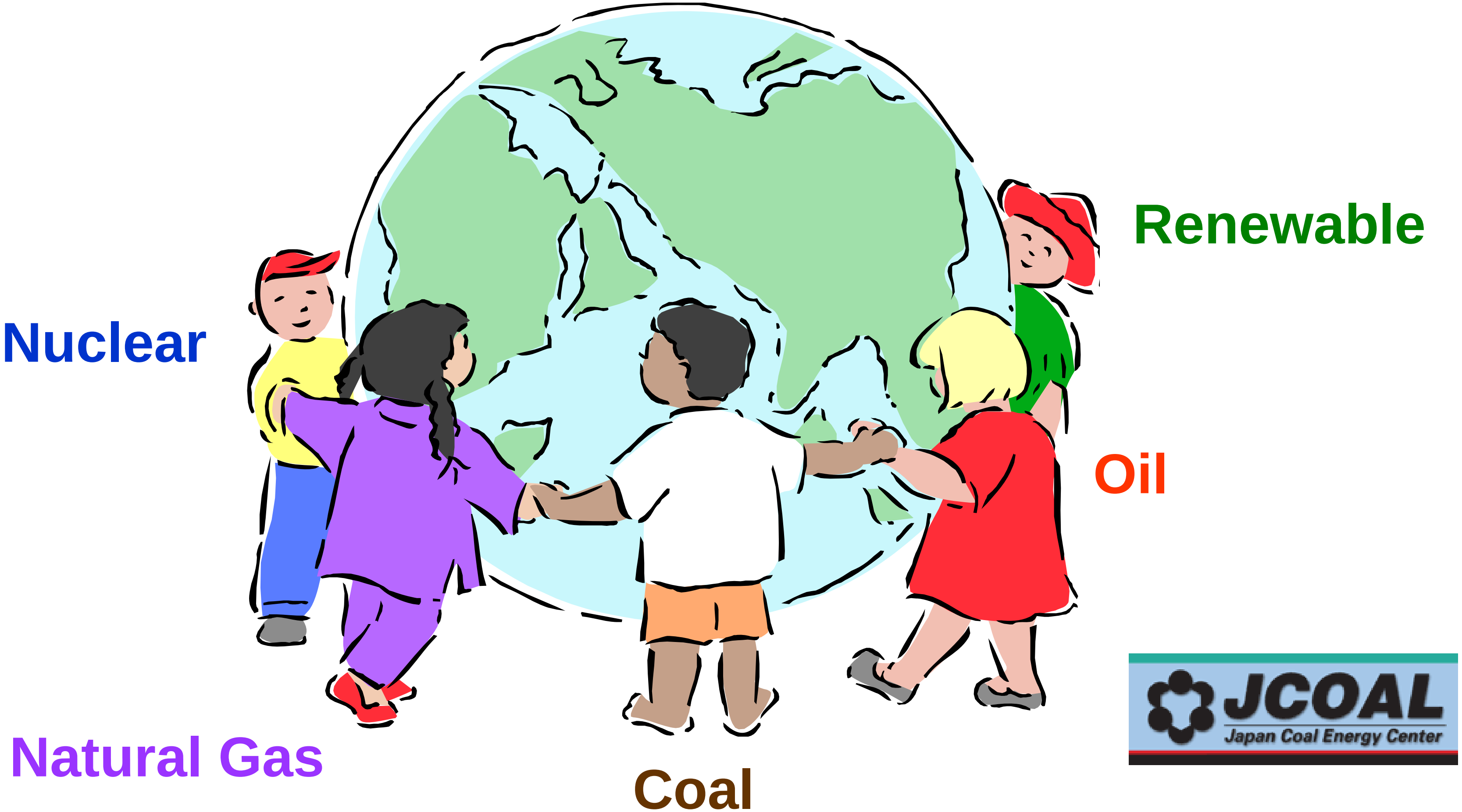


More and more collaborations among researchers of different field !

Concluding Remarks

1. **Oxy-coal combustion is promising option for easy and efficient CO_2 recovery by just applying existing technologies.**
2. **Conversion ratio from Fuel-N to NOx can be automatically reduced to 1/4 - 1/6.**
   (Heat recirculation can significantly enhance this effect.)
3. **Flame propagation velocity decreases to about 1/3 – 1/5.**
4. **Decrease of net efficiency in Oxy-firing can be recovered by combining active CO_2 recovery with IGCC or IGFC.**

We must enhance the value of coal by promoting the Clean Coal Technologies for our future.



Thank you for your attention !

Performance of PF boilers Retrofitted with Oxy-coal Combustion:

Understanding Burnout, Coal Reactivity, Burner Operation and Furnace Heat Transfer

Terry F Wall

Priority Research Centre for Energy & CRC for Coal in Sustainable Development (CCSD), Chemical Engineering, The University of Newcastle, University Drive, Callaghan, NSW 2308, Australia

IEAGHG International Oxy-Combustion Network
Yokohama, Japan, March 5th/6th, 2008

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Priority Research Centre for Energy

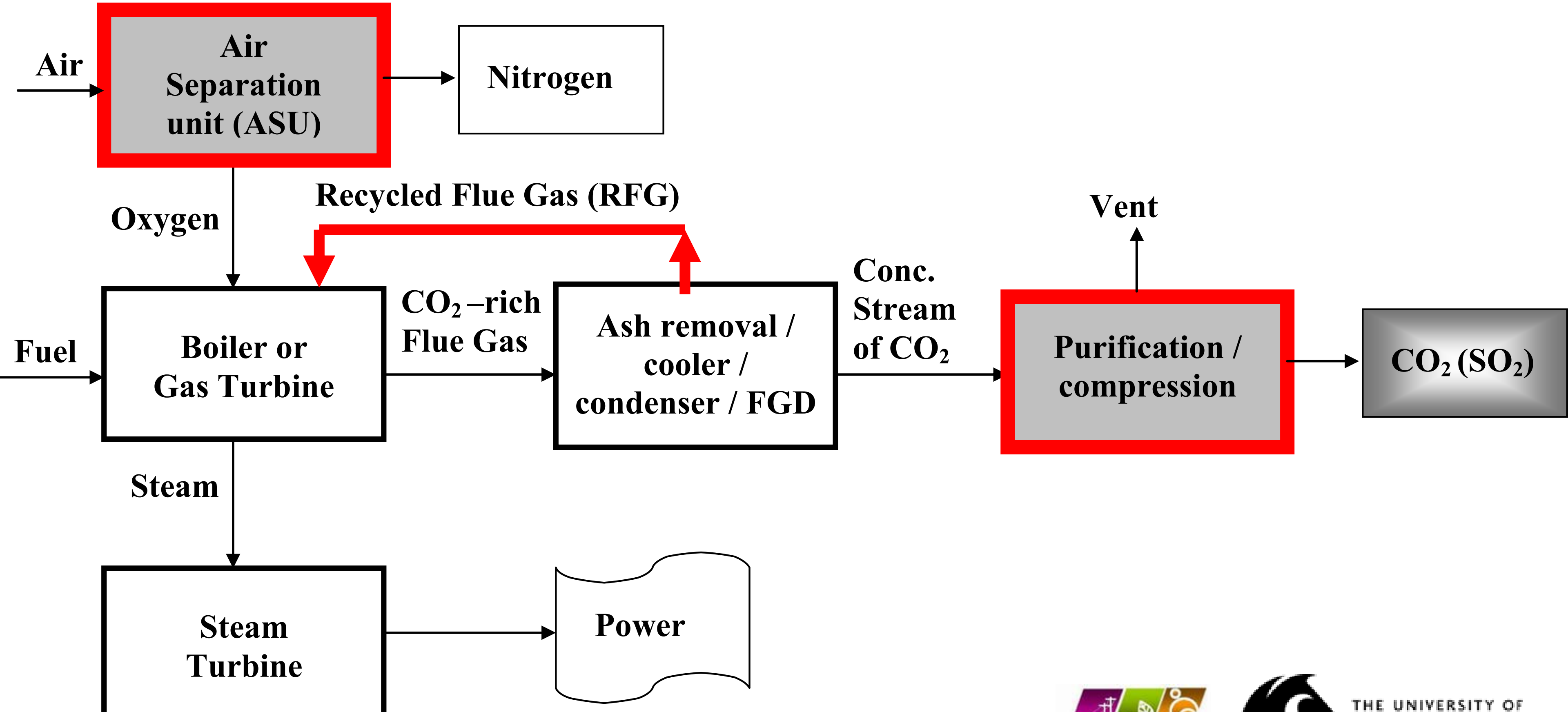
Context and content

Compares air and oxy-fuel furnace performance

Retrofit of an existing air-fired boiler while maintaining heat transfer, considering

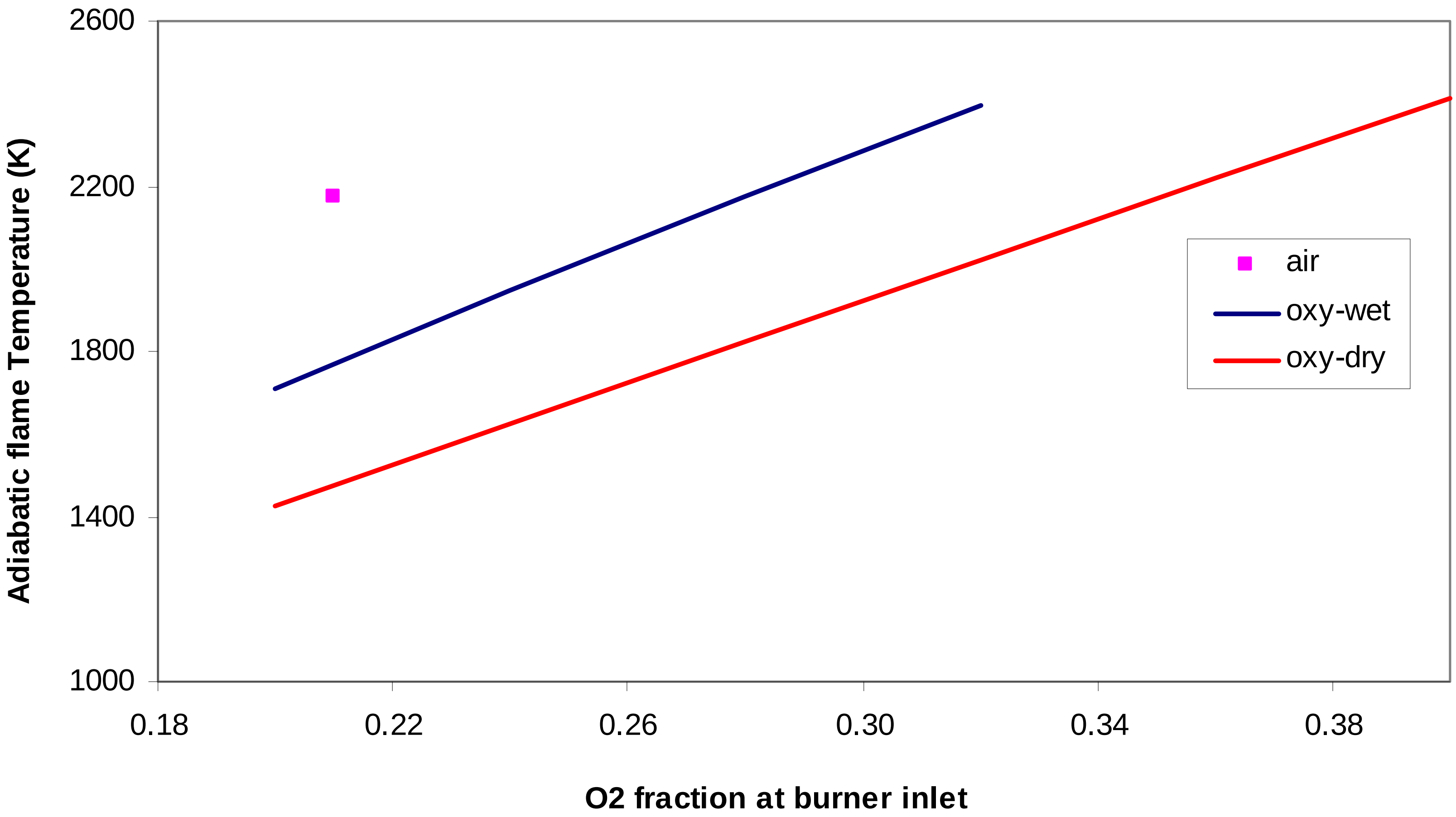
- Conditions for matched heat transfer
- Changed burner flows, with flame and heat transfer impacts
- Coal reactivity and burnout impacts

Oxy- fuel


Air
Air Separation unit (ASU)
Nitrogen
Oxygen
Recycled Flue Gas (RFG)
Vent
Fuel
Boiler or Gas Turbine
CO_2 –rich Flue Gas
Ash removal / cooler / condenser / FGD
Conc. Stream of CO_2
Purification / compression
CO_2 (SO_2)
Steam
Steam Turbine
Power

Heat transfer

AFT


2600
2200
1800
1400
1000
Adiabatic flame Temperature (K)
0.18
0.22
0.26
0.30
0.34
0.38
O2 fraction at burner inlet
air
oxy-wet
oxy-dry

Oxy-fuel: differences of combustion in O_2/CO_2 compared to air firing

- To attain a similar AFT the O_2 proportion of the gases through the burner is ~ 30%

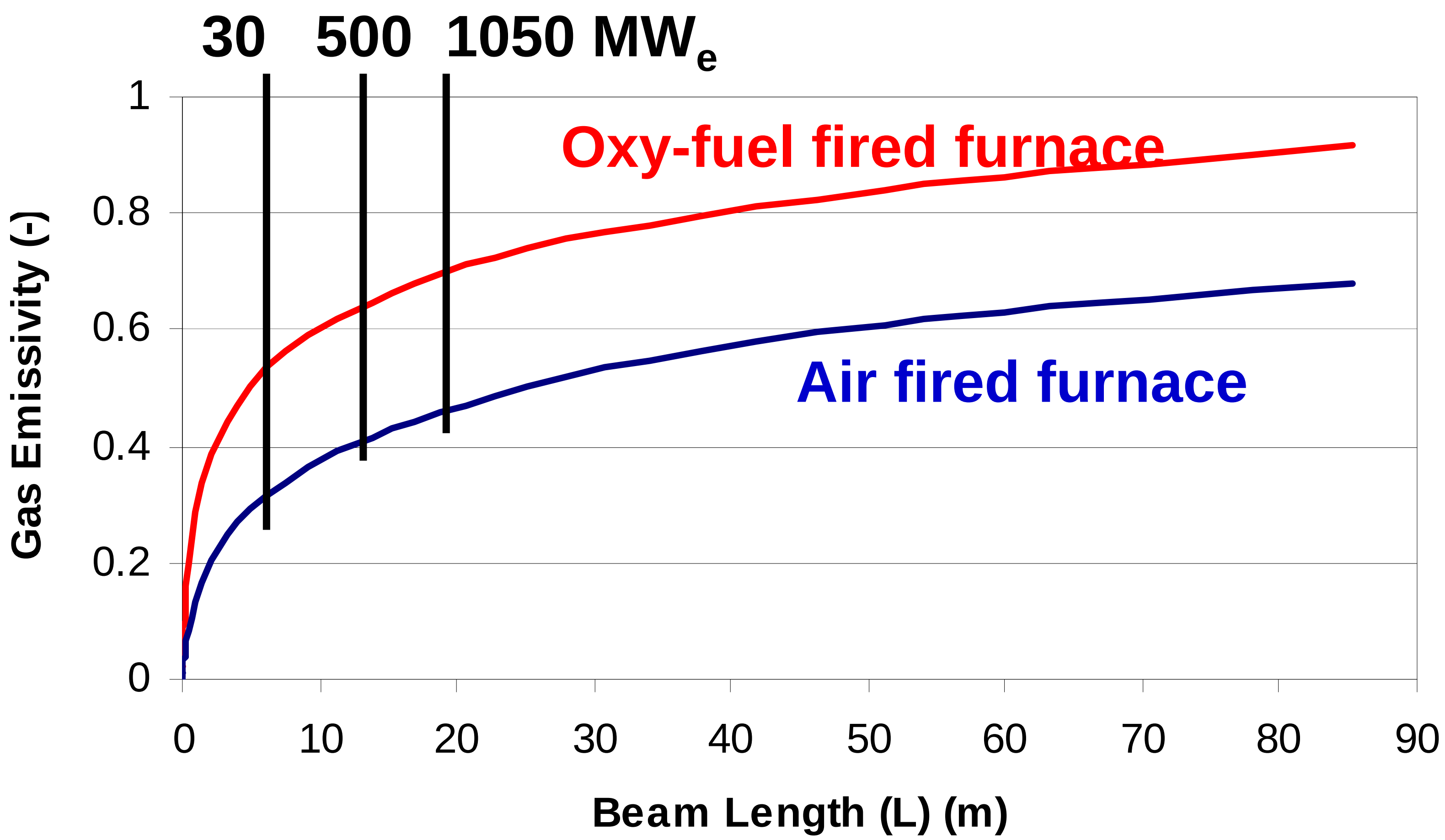
- The high proportions of CO_2 and H_2O in the furnace gases result in higher gas emissivities

- The volume of gases flowing through the furnace is reduced

- The volume of flue gas (after recycling) is reduced by about 80%.

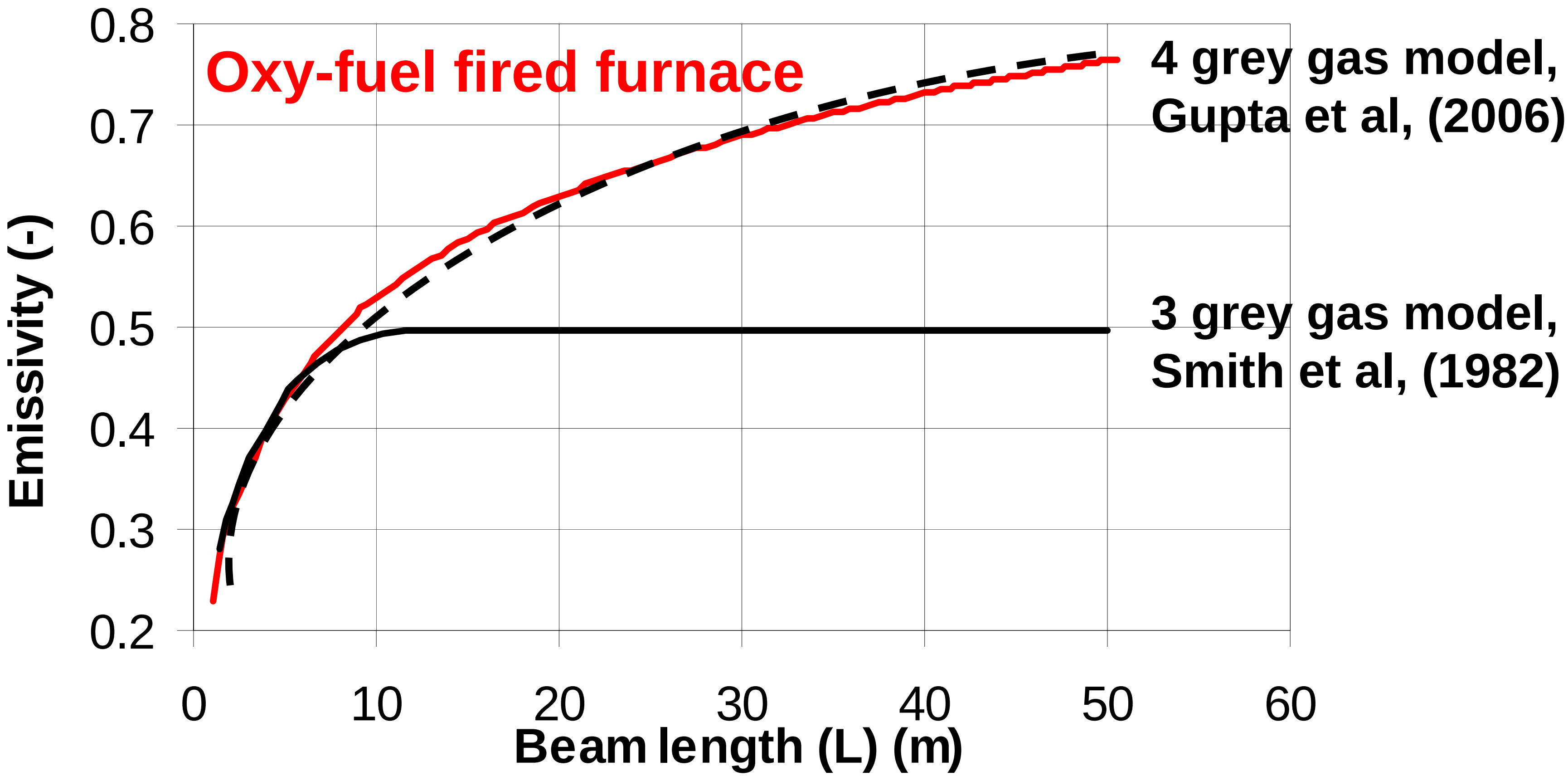
- Recycle gases have higher concentrations in the furnace

Gas property differences 1: Emissivity
Triatomic gas (H_2O+CO_2) emissivity ~ beam length comparisons



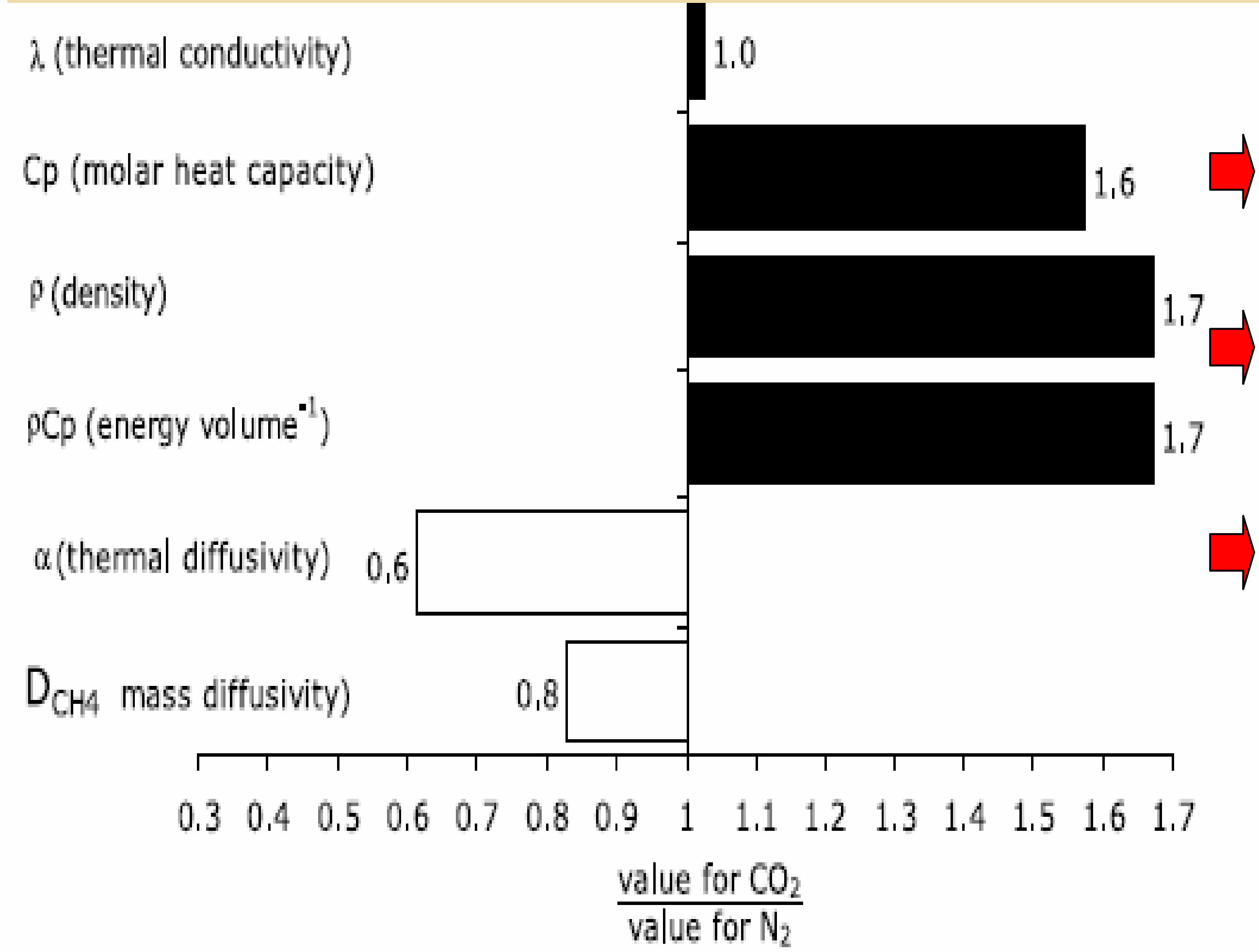
Gupta et al (2006)

CFD radiative transfer inputs



$$\varepsilon = \sum_{i=0} a_{\varepsilon,i}(T)\,[1 - e^{-k_i (p_{CO2} + p_{H2O}) L}]$$

Gas property differences 2: Heat capacity etc



Gas property ratios for CO_2 and N_2 at 1200 K

Impact for air to oxyfuel retrofit

- Higher O2 thru burner
- Lower burner velocity, higher coal residence time in furnace
- Slower flame propagation velocity

Properties from Shaddix, 2006

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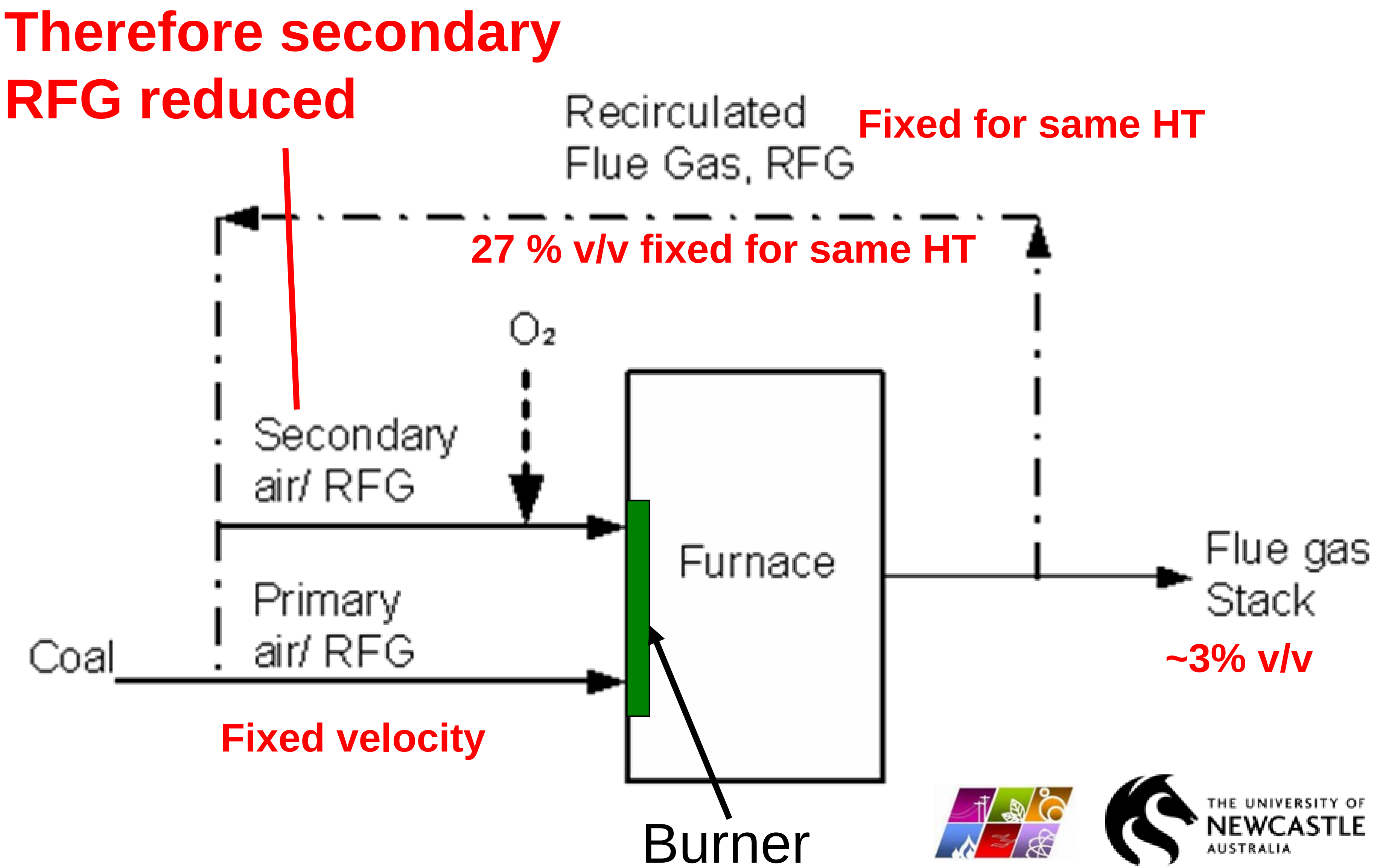
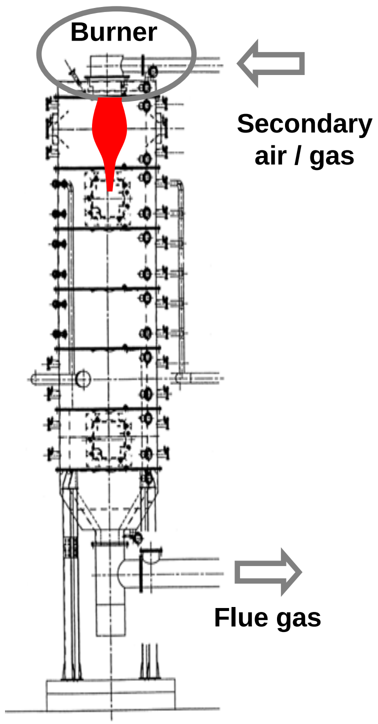
Burner flow comparisons for a retrofit



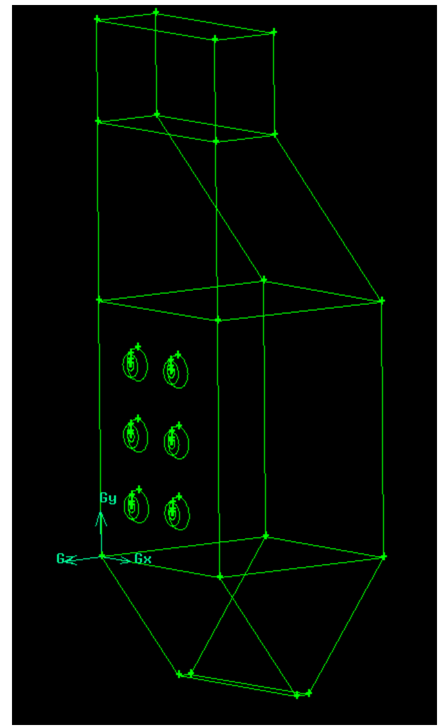
Furnaces considered

Pilot scale- 1MWt



Furnace output:	1.2 MWt
Furnace size :	ID – 1.3 m & L – 7 m
Burner :	1 Swirl burner (sec) & Small burner Quarl
Tests:	Air & Oxy-firing

Utility scale-30 MWe



Furnace output:	30 MWe
Furnace size :	6.1 m X 6.7 m X 21.5 m
Burner :	6 Swirl burners & burner Quarl
Tests:	Air & Oxy-firing

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1 MWt test conditions

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

Preheated air/RFG: primary 350 - 400K and secondary 450 - 550 K, Wall 1200 K

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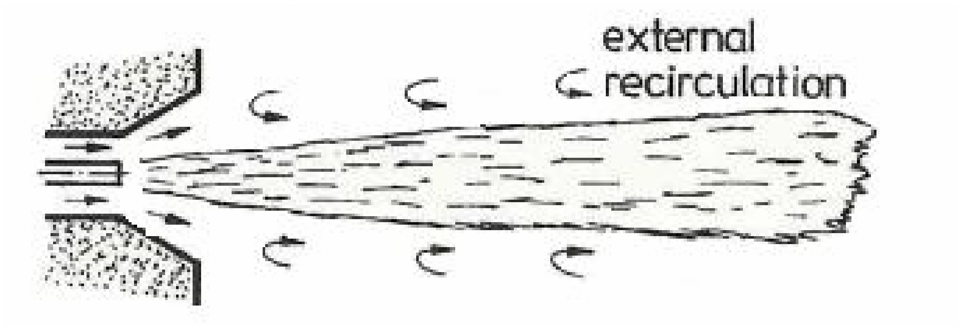
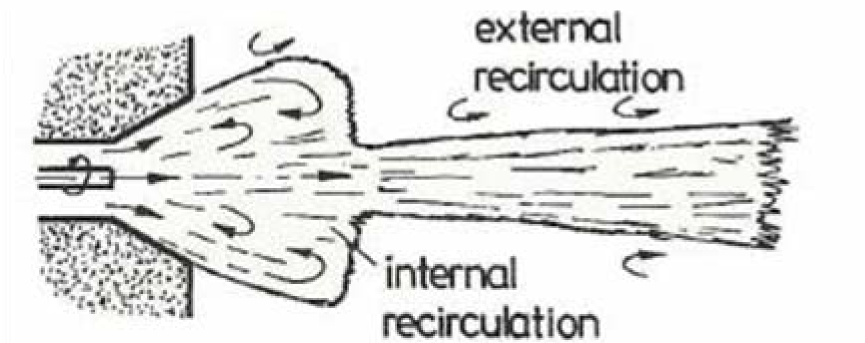
IFRF Flame types from swirl burners

Type-0



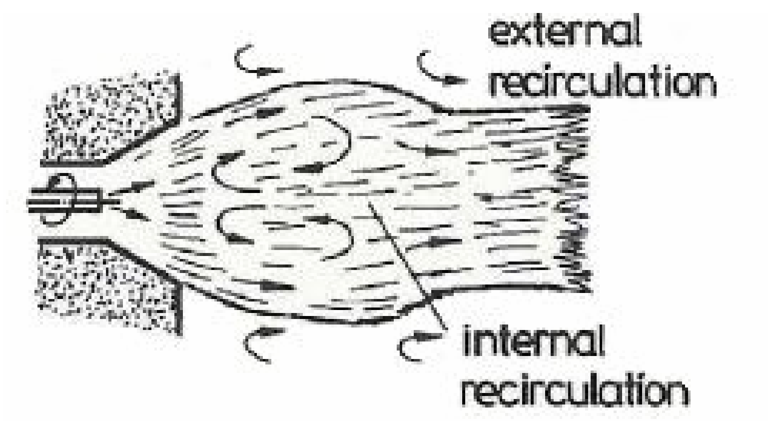
Lo S

Type-1



Hi S (S>0.6) ,
Lo v_2

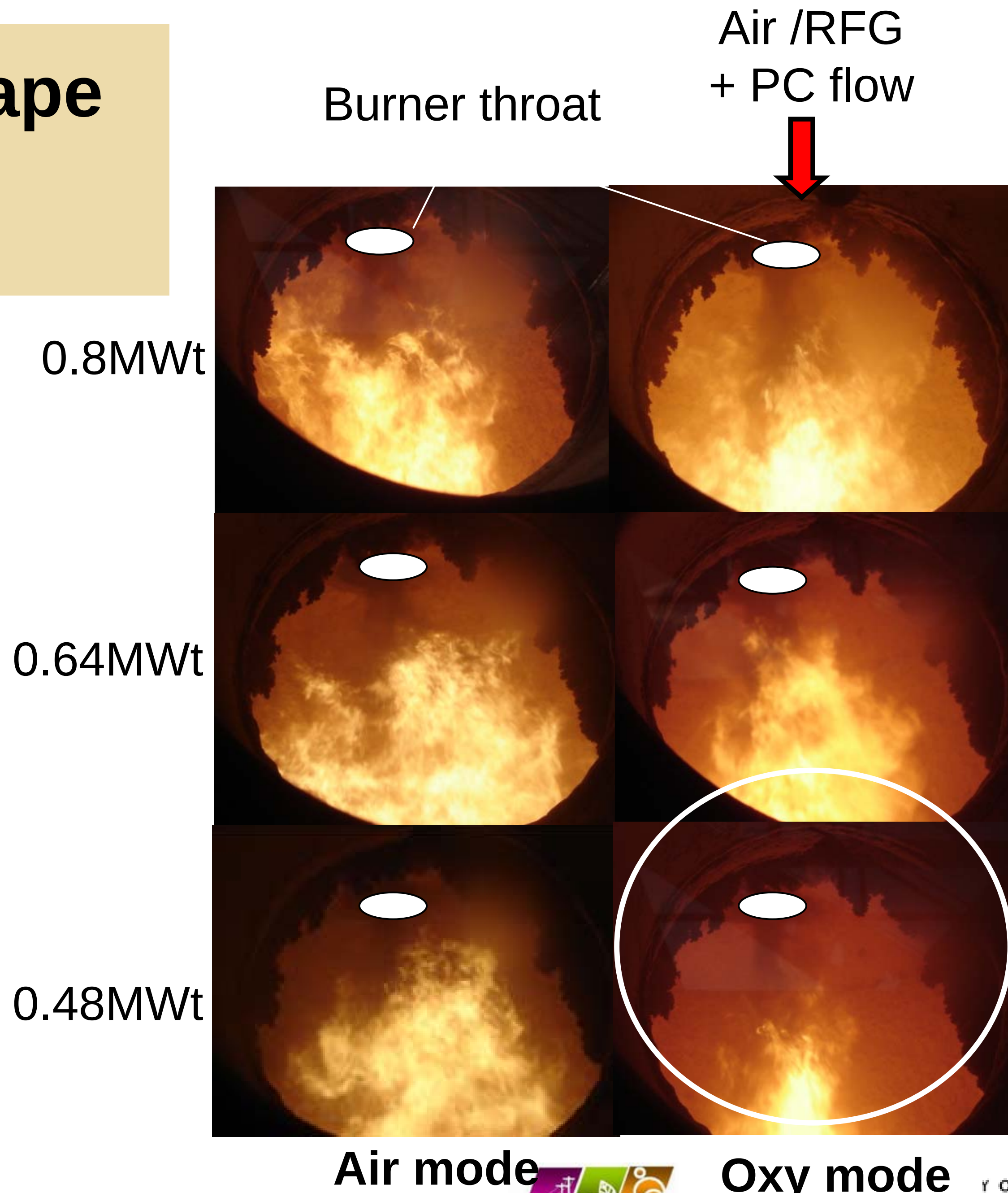
Type-2



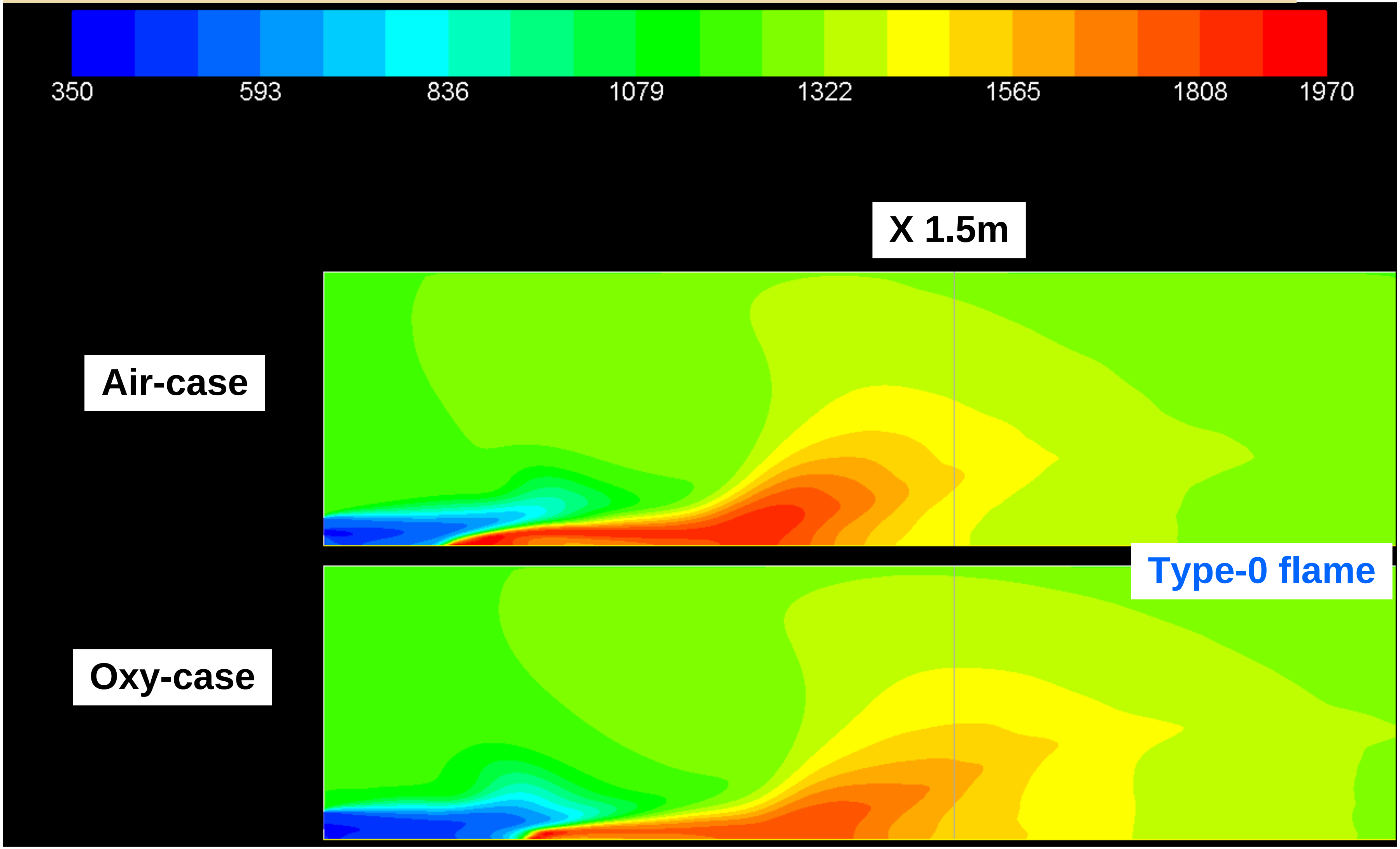
Hi S, Hi v_2

1 MWt: Flame shape & ignition delay

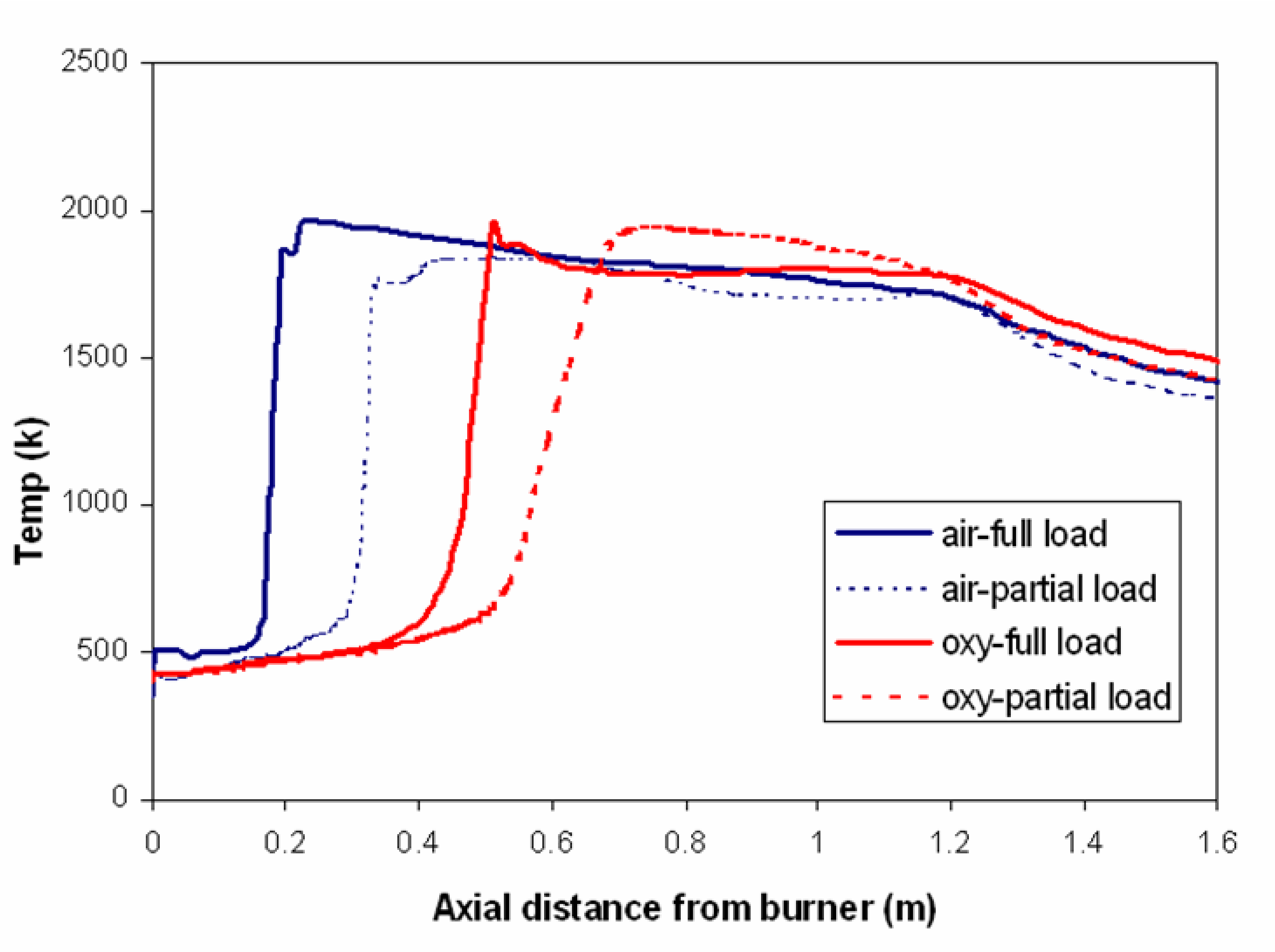
- All Type-0 flames
- Difficult to distinguish between combustion modes
- Ignition delay in partial load – oxy case



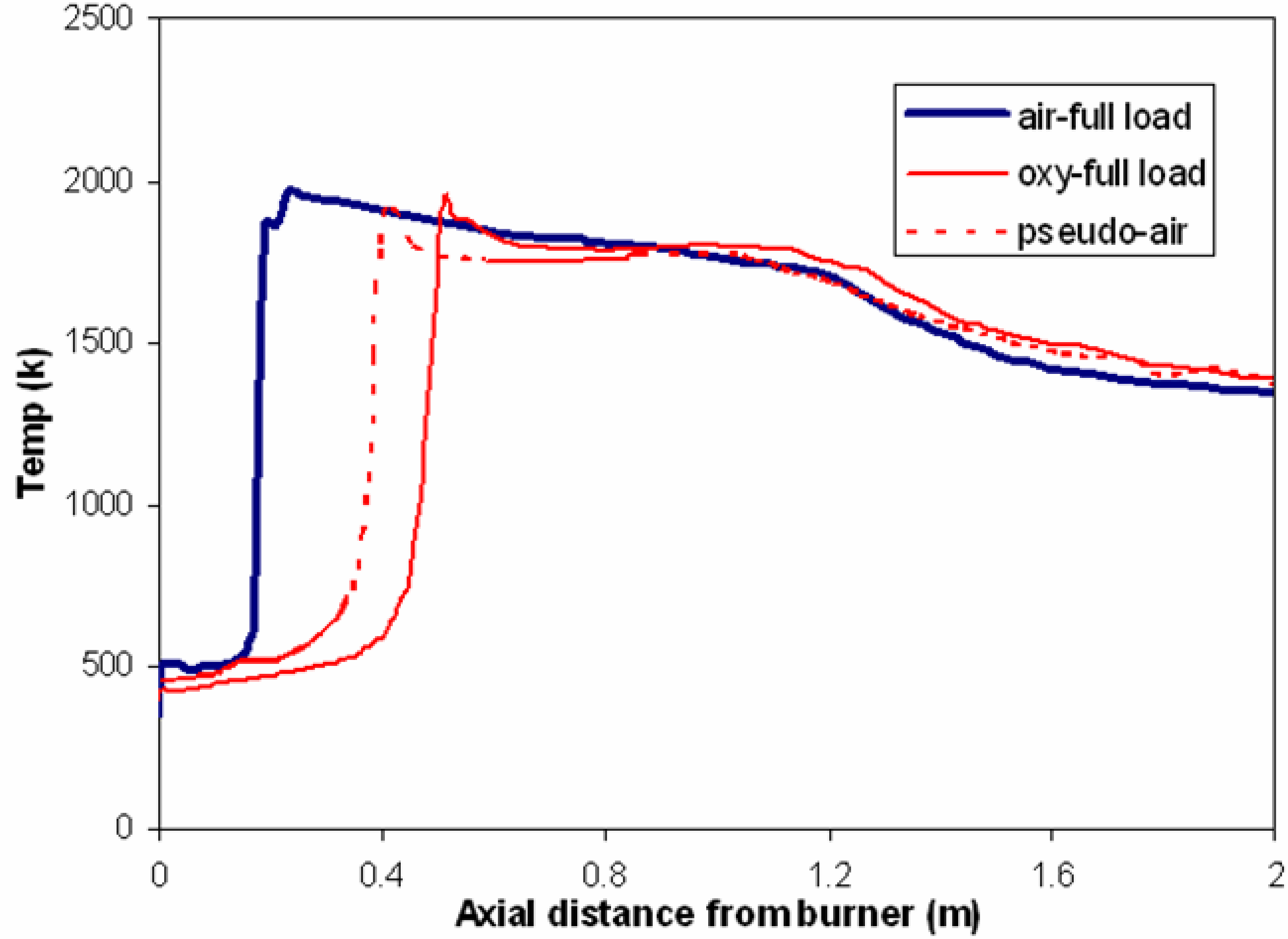
1 MWt – Temperature contours at full load



Sensitivity analysis – full & partial load



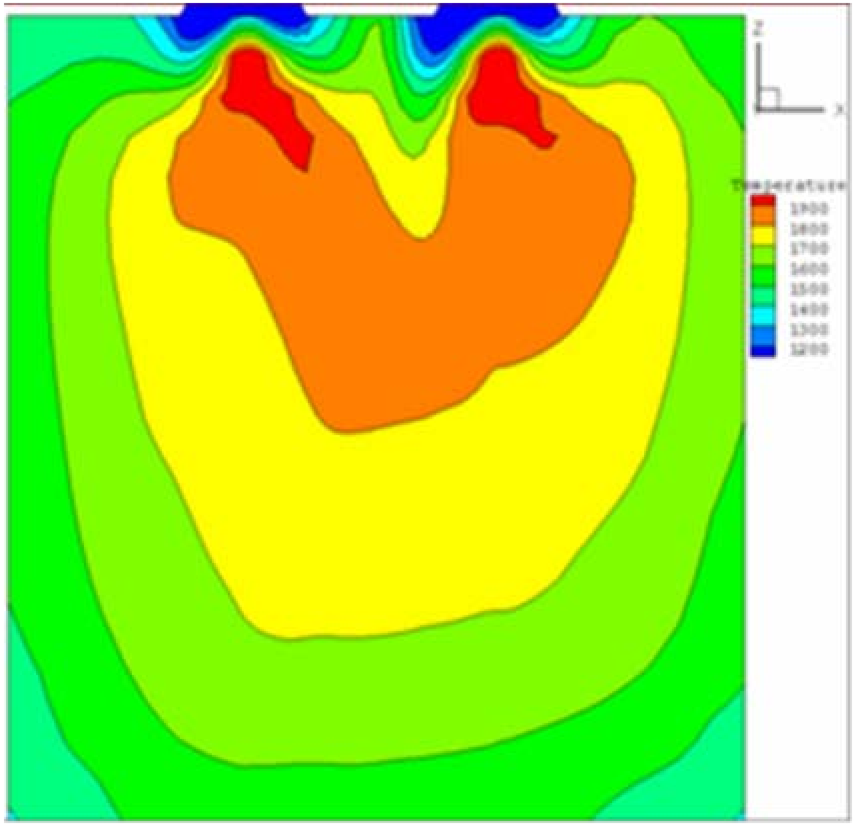
Effect of momentum flux



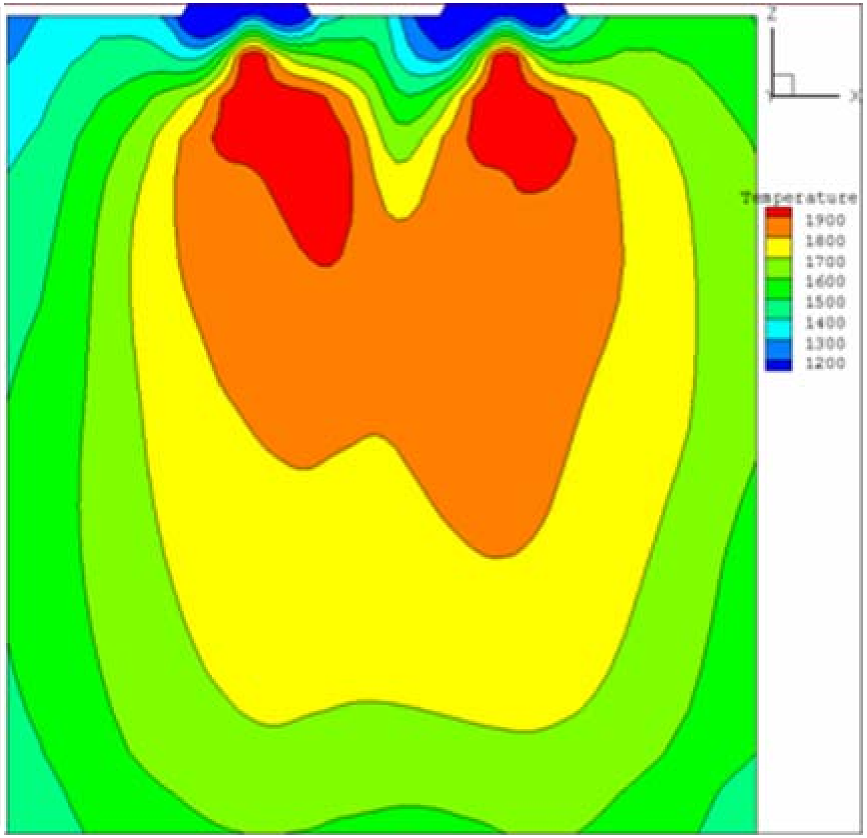
✓ Confirms the significance of **momentum flux** and **Gas properties** on flame ignition

30 MWe Burner plane – Temperature contours

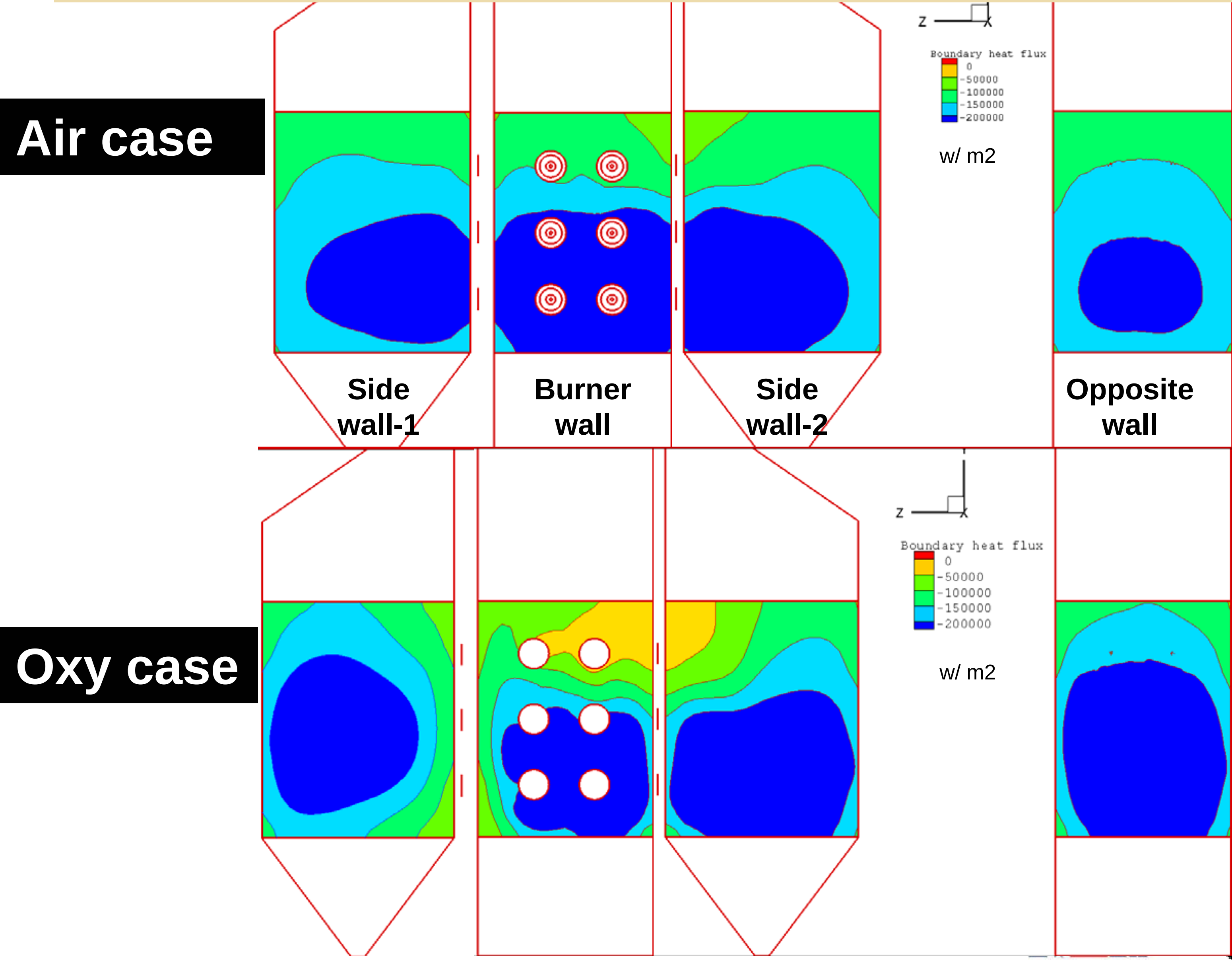
Air case



Oxy case



30 MWe Heat flux contours



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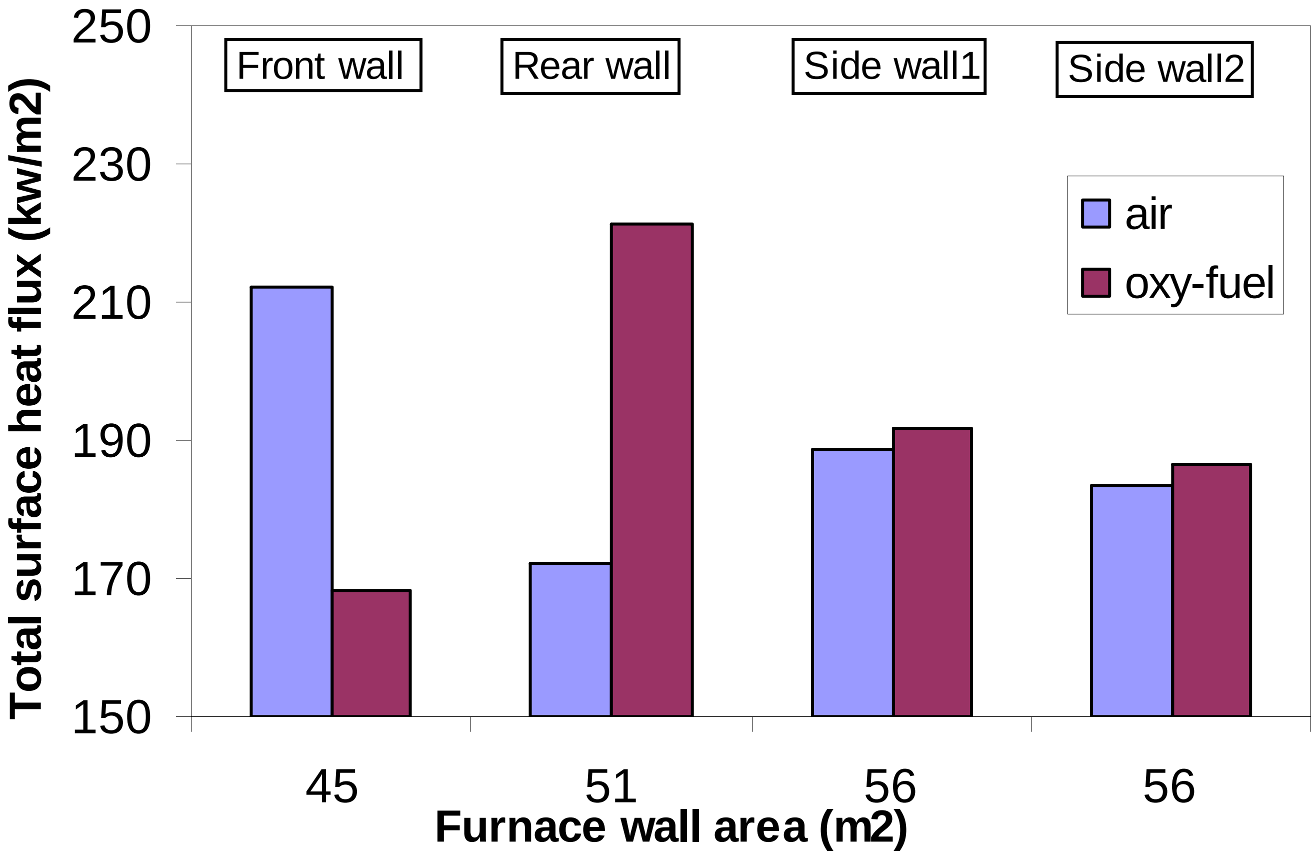
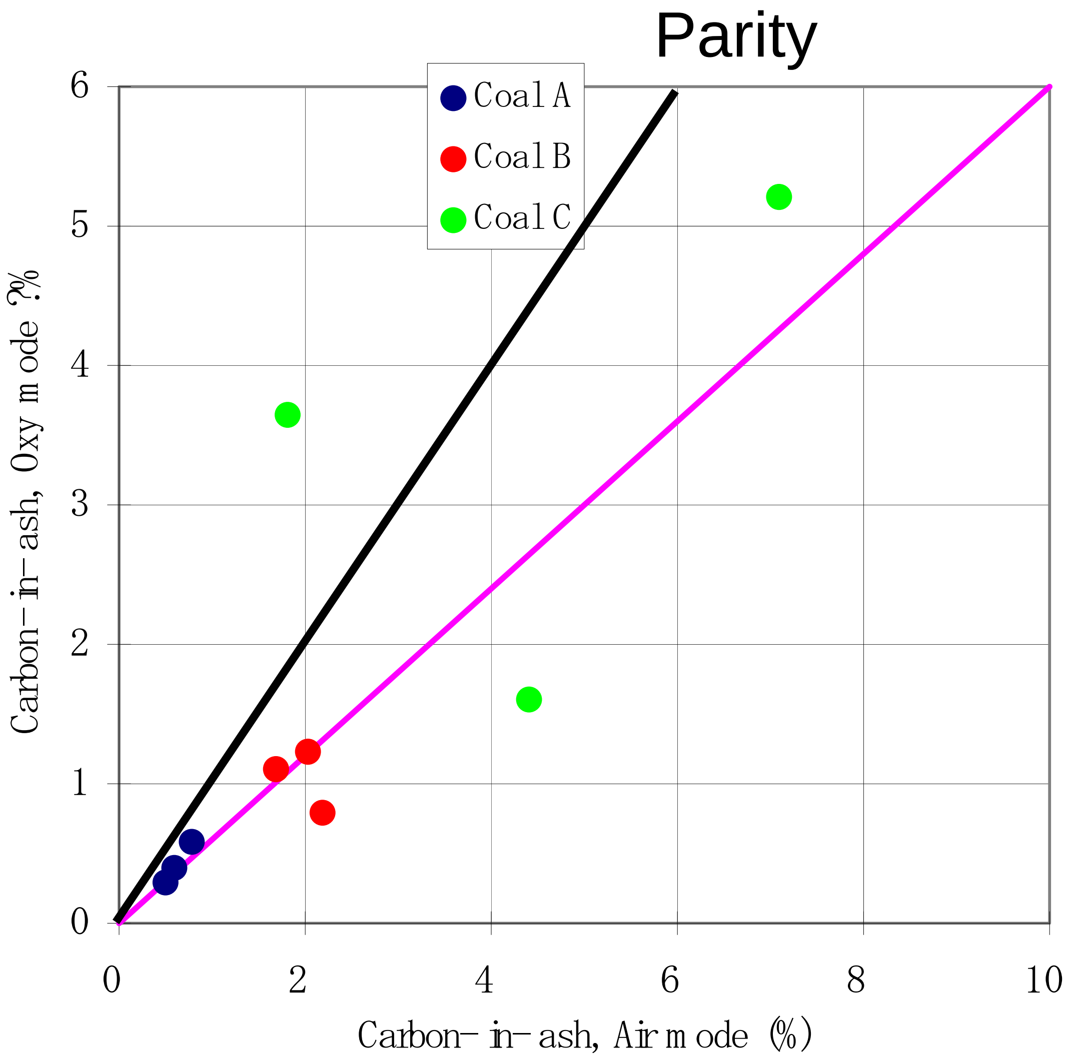
30 MWe – heat transfer results



Coal burnout and reactivity

1 MWt Combustibility comparison



Illustrative differences in air and oxyfuel which influence burnout

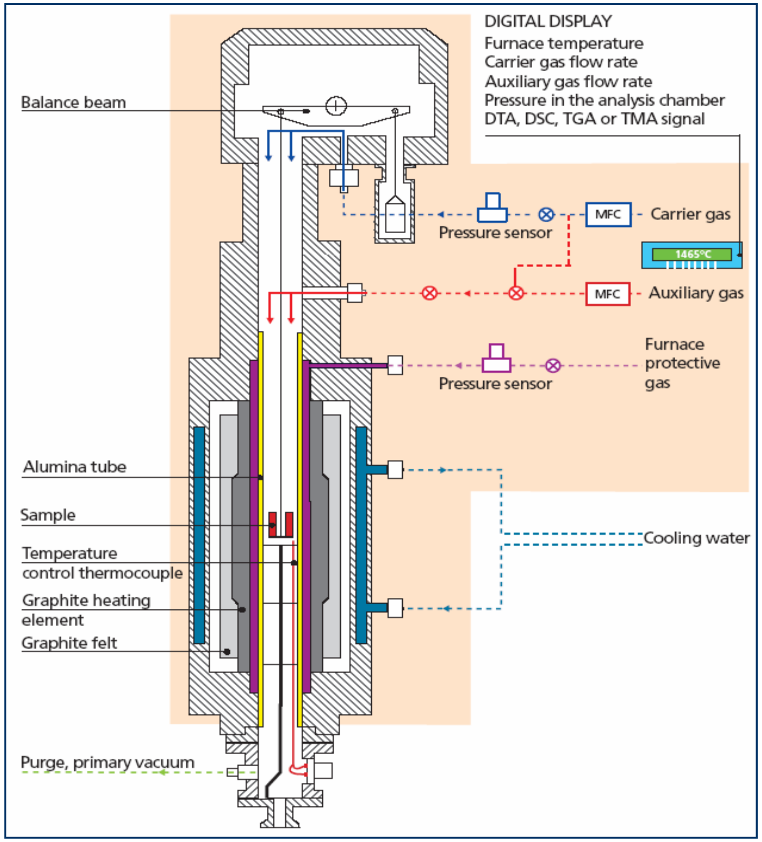
For matched furnace heat transfer:

Oxyfuel has longer furnace residence time, ~20%

Oxyfuel has lower temperatures, ~ 50 oC

In oxyfuel, coal experiences an environment with higher O2

Experimental techniques



TGA - Low temperature reactivity measurements

DTF – High temperature reactivity measurements

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Coal properties

Size range +63-90 µm	Australian Semi- Anthracite (Coal A)	Australian Bituminous (Coal B)
Proximate Analysis wt.% (air dried basis)		
Air-dried moisture	1.7	8.0
Ash	9.8	19.9
Volatile Matter	8.7	25.6
Fixed Carbon	79.8	46.5
Ultimate Analysis wt.% (daf basis)		
Carbon	91.4	79.1
Hydrogen	3.77	4.51
Nitrogen	1.88	1.16
Sulphur	0.76	0.24
Oxygen	2.2	15.0

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Experimental conditions

GAS ATMOSPHERES

Pyrolysis – 100% N_2 and 100% CO_2
Combustion -
  Air – 21% O_2 v/v basis in N_2
  Oxy – 21% O_2 v/v basis in CO_2

EXPERIMENTAL CONDITIONS

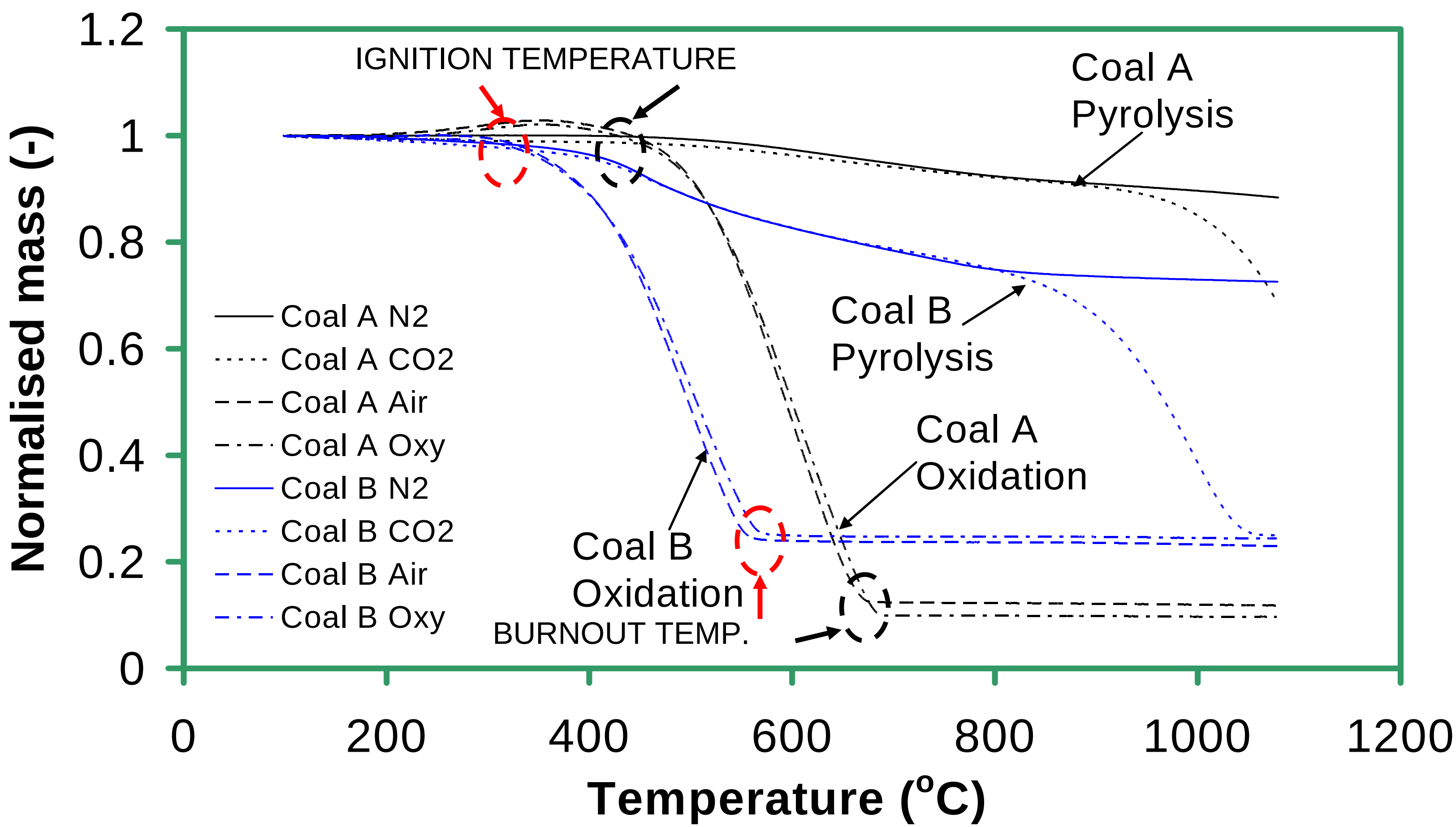
TGA

Parameter	Condition
Sample mass (coal)	10 mg
Temperature range (non-isothermal)	30 to 1100 ^oC
Heating rate	10 ^oC /min
Gas flow rate	70 mL/min

DTF

Parameter	Condition
Coal feed rate	4 to 5 g/h
Total gas flow rate	5.2 L/min
Gas temperature	1400 ^oC
Oxygen concentration in N_2/CO_2	3 to 30 % v/v basis

Ignition & burnout temperatures of Coal A & Coal B in TGA



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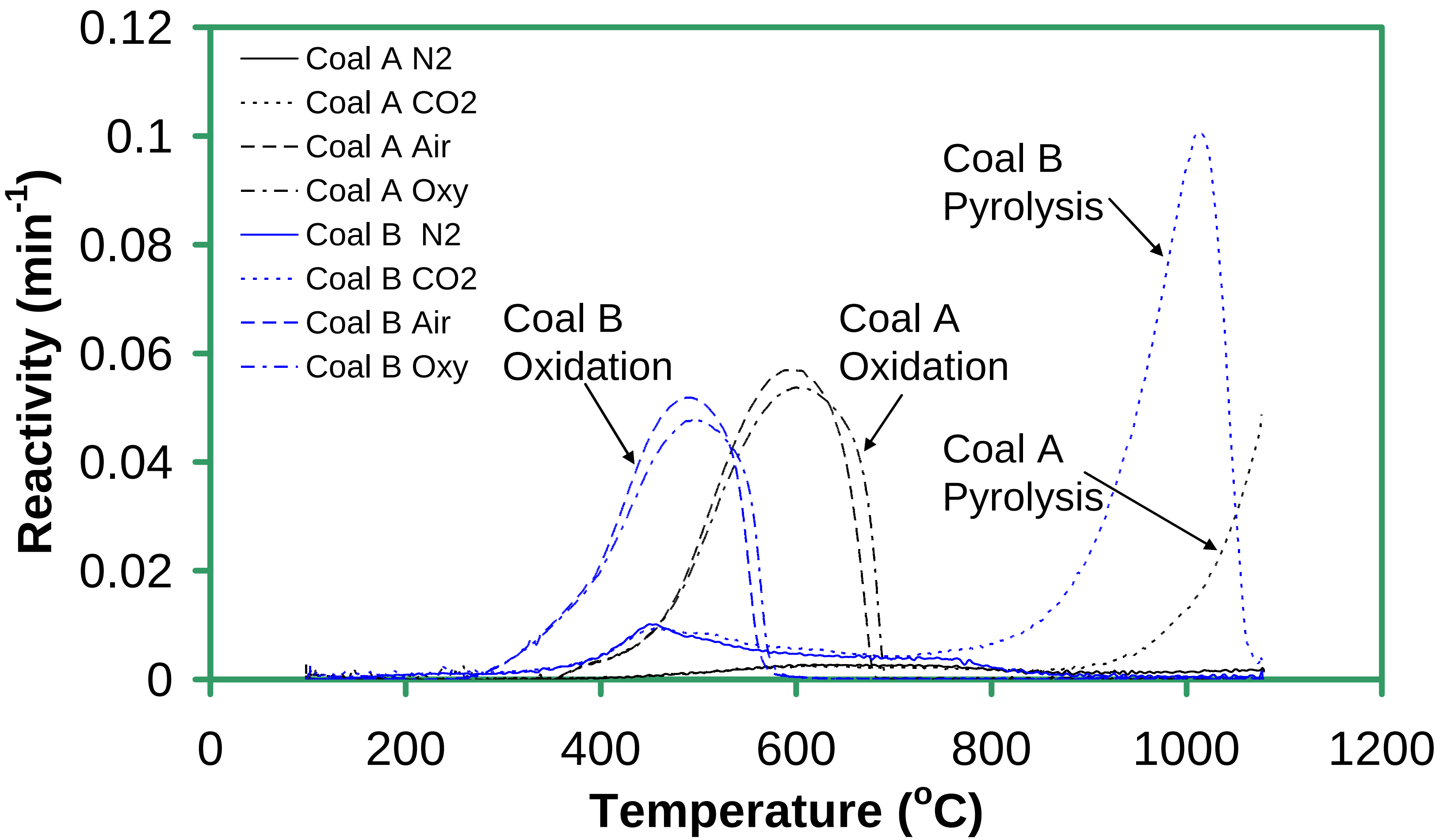
Pyrolysis and oxidation reactivities of Coal A & Coal B in TGA



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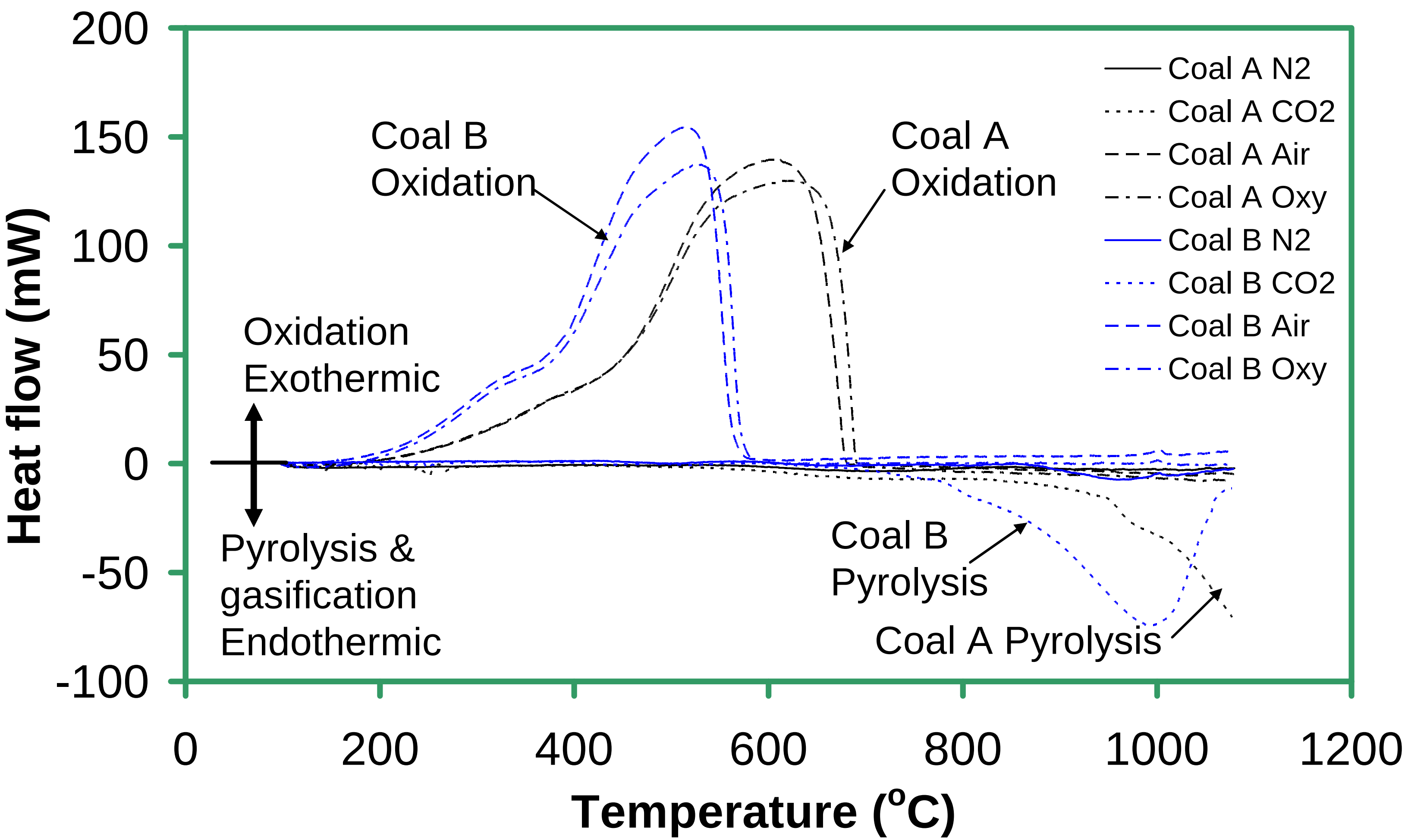
Heat flow during pyrolysis & oxidation of Coal A & Coal B in TGA

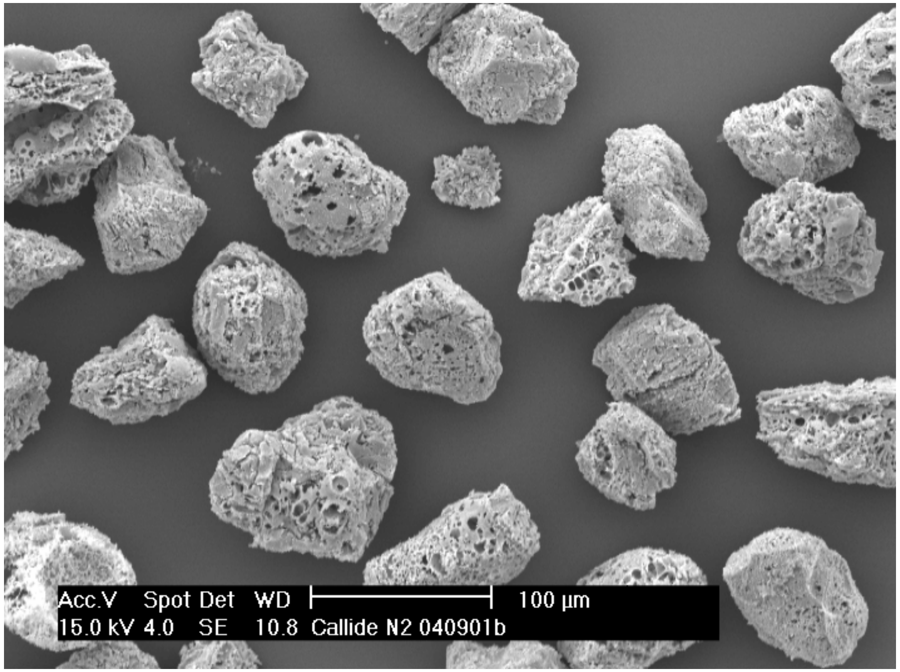


Volatile yields at 1400 oC

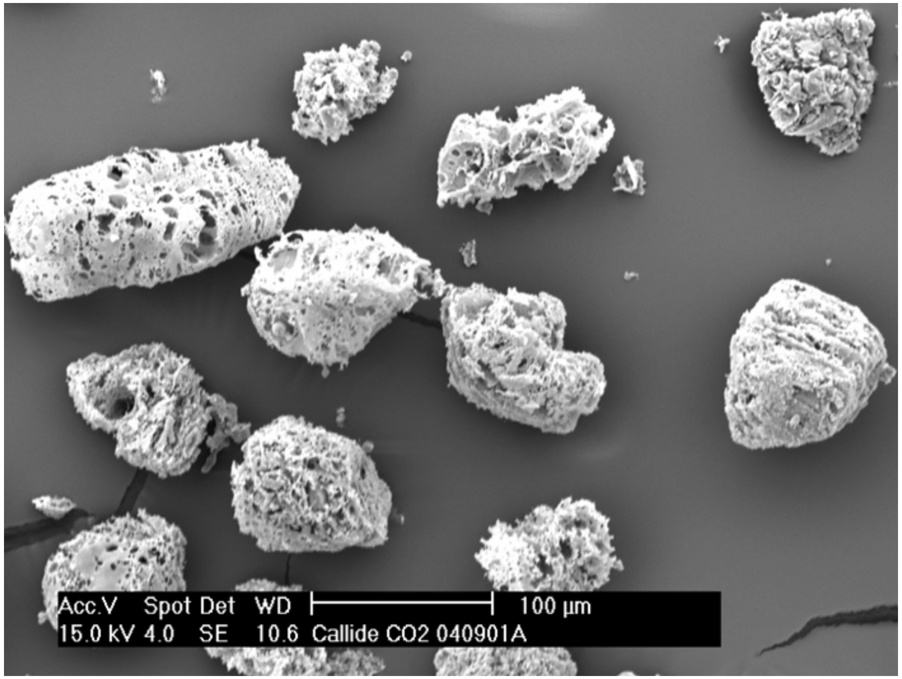
	Coal B	Coal C	Coal D
V* (N_2)	36.7	30.9	53.5
Q factor (N_2)	1.52	1.43	1.76
V* (CO_2)	43.3	32.2	66.2
Q factor (CO_2)	1.79	1.49	2.18

V* - Volatile yield at 1400 ^{o}C
Q factor – Ratio of V* and volatile yield obtained by proximate analysis

SEM pictures of N_2 & CO_2 chars formed in DTF at 1400 °C using Coal B



100% N_2



100% CO_2

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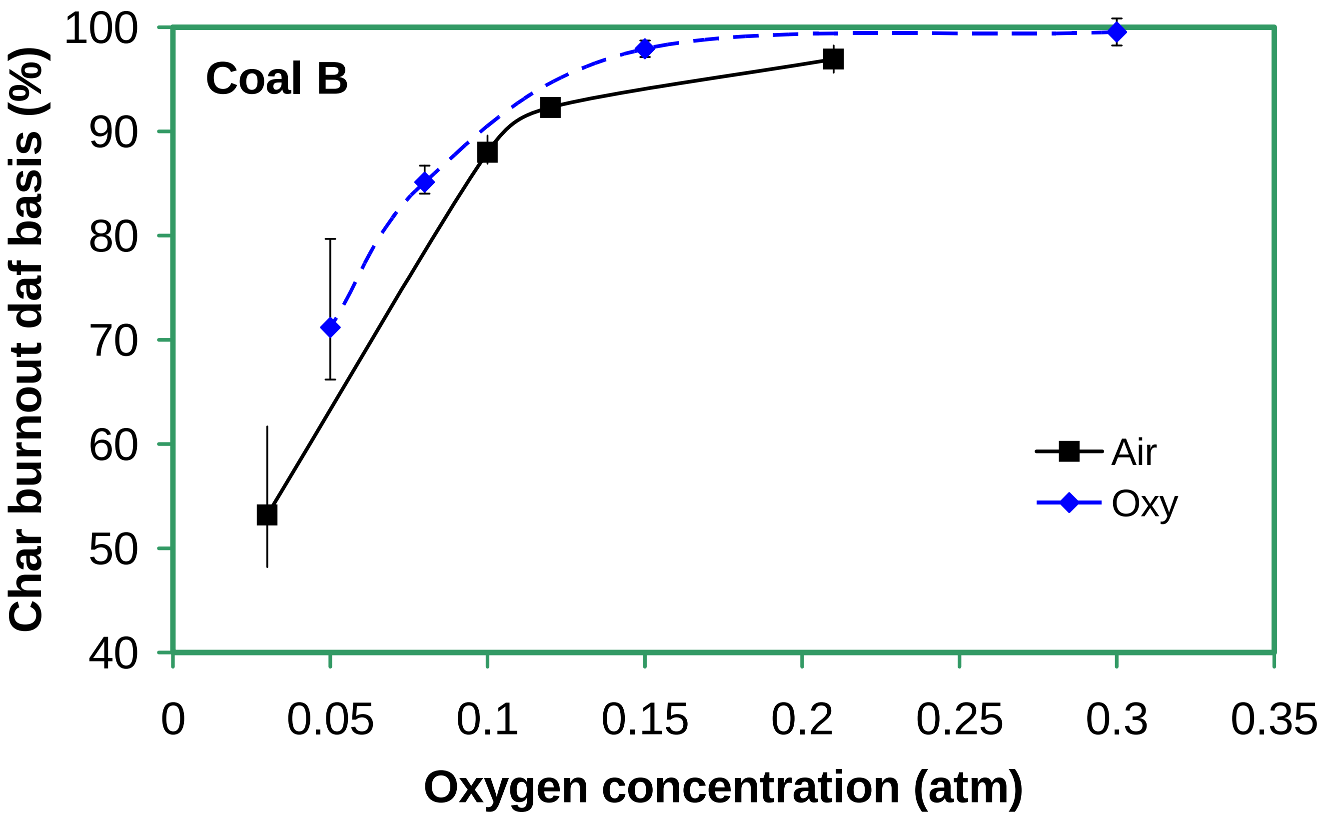
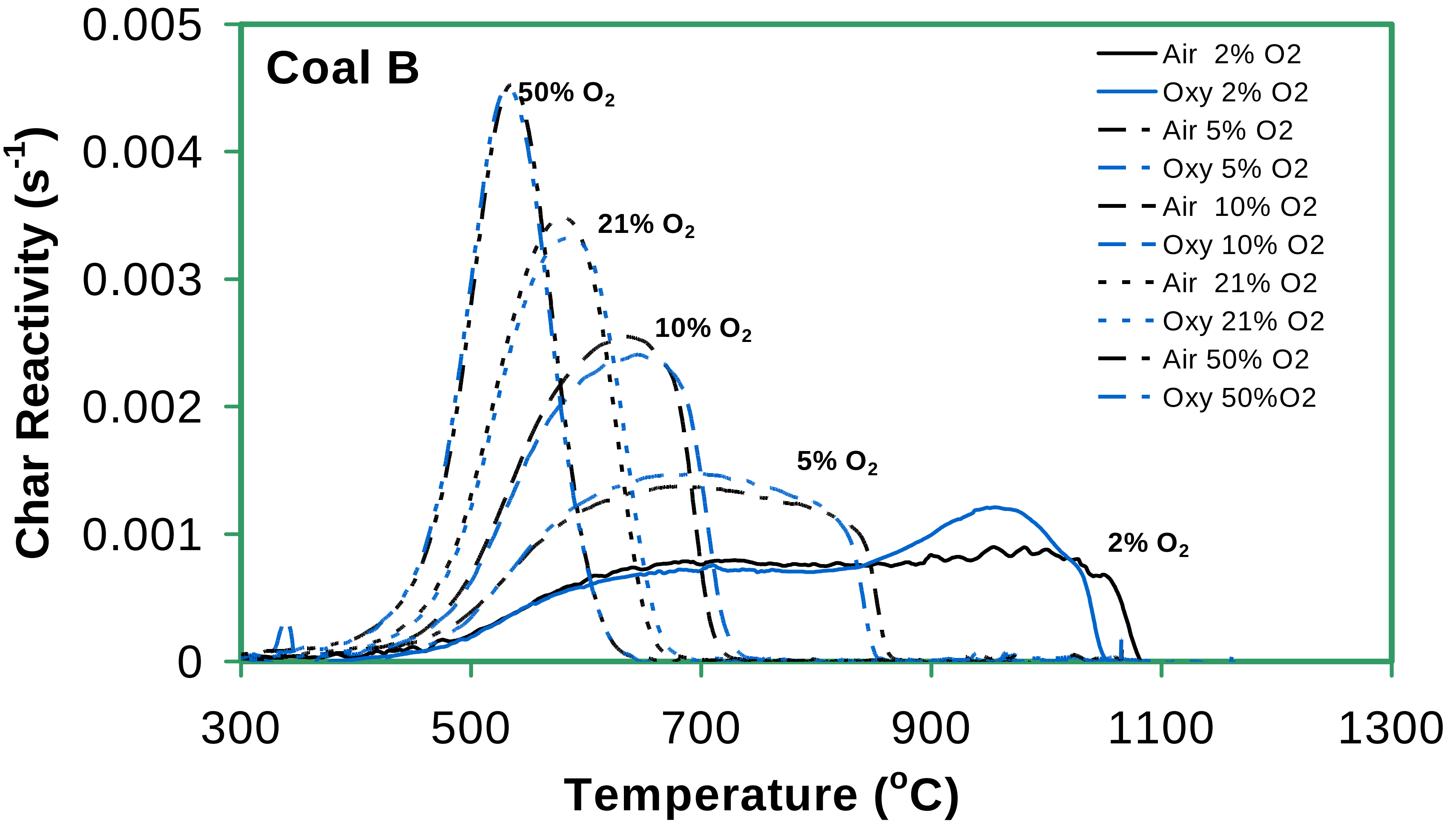
Char burnout in DTF taking V*(N_2) to estimate char yield

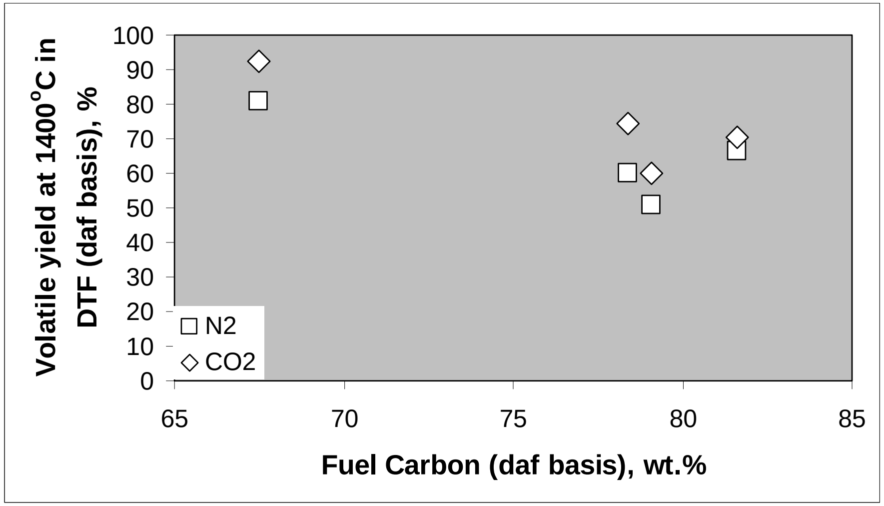


DTF-char reactivity in TGA

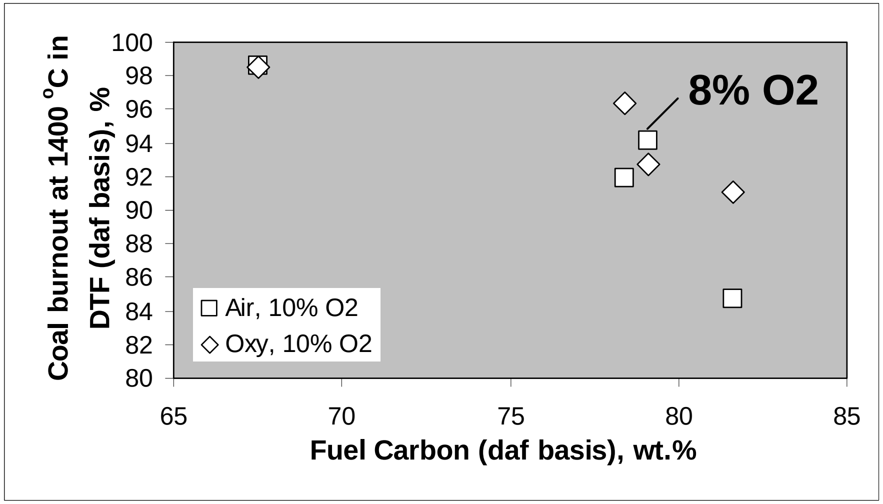


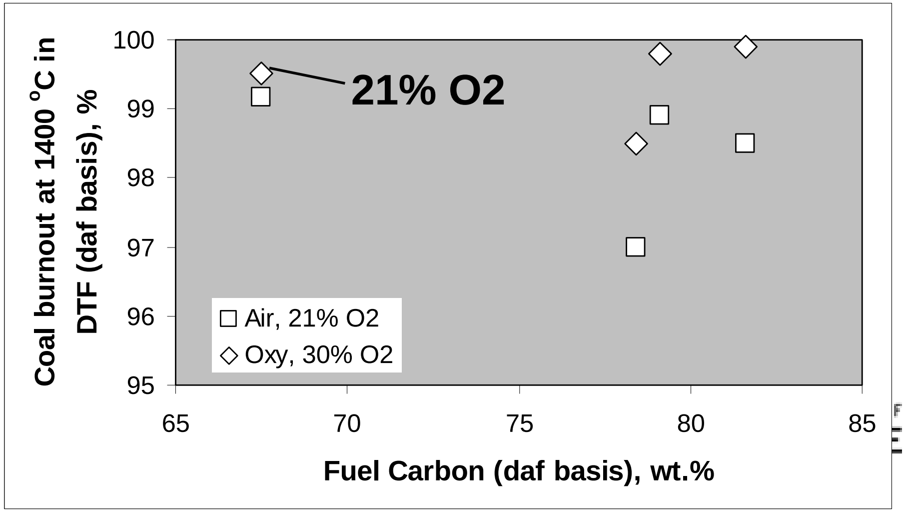
Summary of reactivity data for 63-9) micron size cuts of four coals from DTF experiments at 1400 °C

Volatile yield in N2



Coal Burnout





Closing comments on impacts and effects in retrofits

Burner aerodynamics are changed for the air burners used in a retrofit

Heat transfer and aerodynamics are interrelated

Oxyfuel radiative transfer cfd prediction models have been developed

… and are now extending to a 400 MWe furnace

Improved burnout is expected and measured in retrofitted oxyfuel boilers, with mechanisms which can improve and worsen burnout

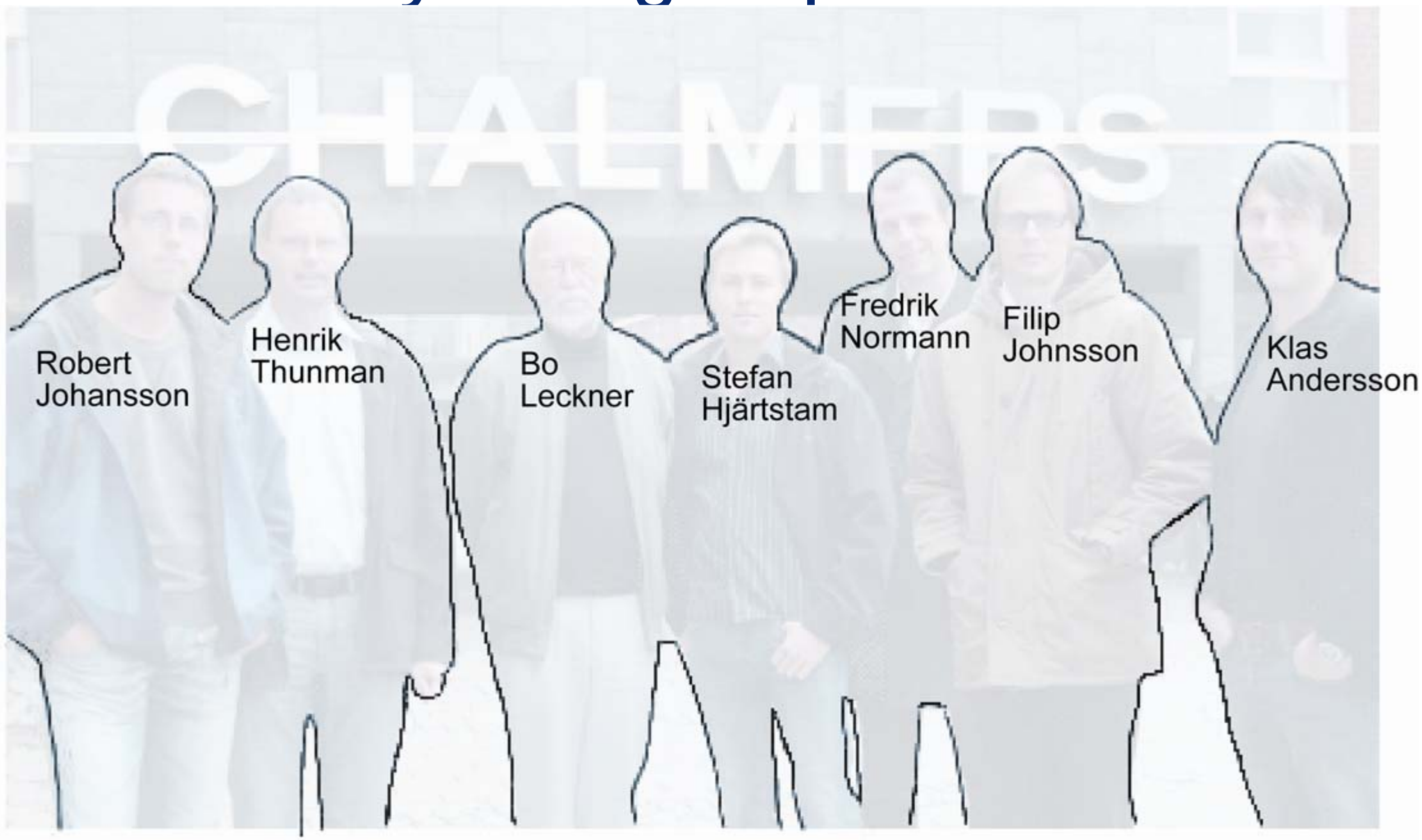
… and reactivity - as volatile yield and coal burnout - in oxyfuel conditions is greater than in air

Evaluation of gas radiation modeling in oxy-fired furnaces

Robert Johansson

Department of Energy and Environment
Chalmers University of Technology

The oxy-fuel group at Chalmers



Missing on the picture: Daniel Fleig
Daniel Kühnemuth

- Collaboration with Vattenfall, FLUENT and IVD (Uni-Stuttgart), Alstom and DOOSAN Babcock etc.

Oxy-fuel research at Chalmers

Primary objective: Obtain knowledge of need for scaling of the process

Focus areas

- Combustion chemistry: nitrogen, sulphur
- Heat transfer
- Fluid mechanics

Propane and lignite fired tests: Identify and characterize differences between oxy-fuel and air combustion conditions

Modeling:
- More detailed modeling of gas radiation, NOx chemistry and sulphur chemistry in connection to the experiments
- CFD-studies

Outline

- Introduction
- Modeling theory
- Experiments
- Results
- Conclusions

Background

Radiation heat transfer is of major importance in design of furnaces

Changed combustion conditions will affect the gas radiative heat transfer

- Longer pressure path lengths
- Different ratio of H_2O/CO_2

Purpose of the modeling work

Evaluate radiation models for conditions relevant to oxy-fired furnaces

Recommend models for CFD-calculations

Provide a tool that can be of help for evaluation of intensity measurements

Solve the radiative transfer equation (RTE) neglecting scattering

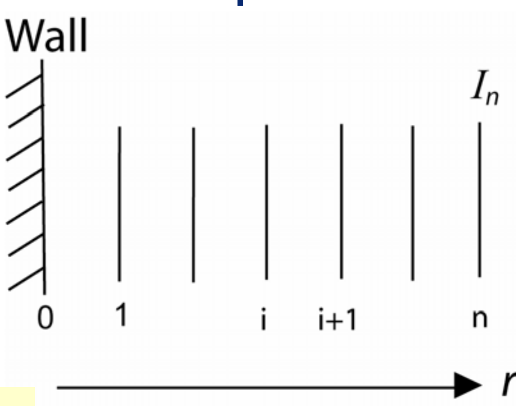
$$\frac{dI_\nu}{dr} = \kappa_\nu I_{b,\nu} - \kappa_\nu I_\nu$$

Change of intensity

Increase of intensity due to emission

Decrease of intensity due to absorption

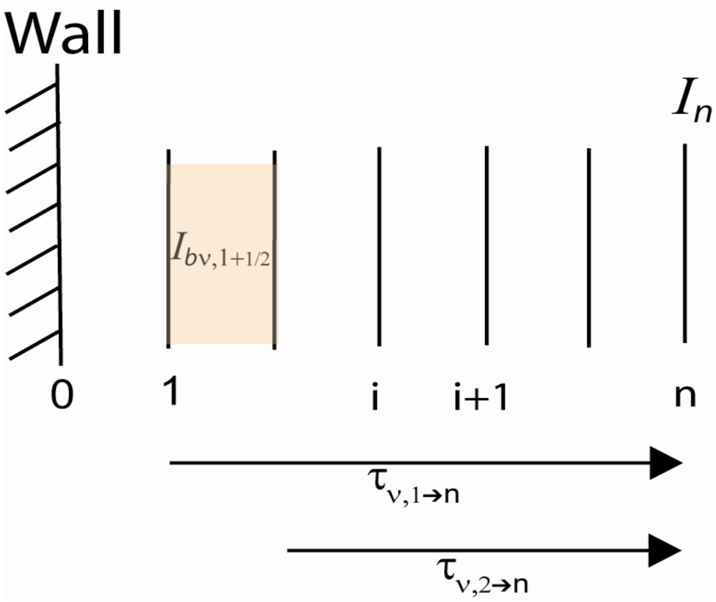
Discretization of a path in homogeneous cells



Correlated formulation

formal solution
physically correct

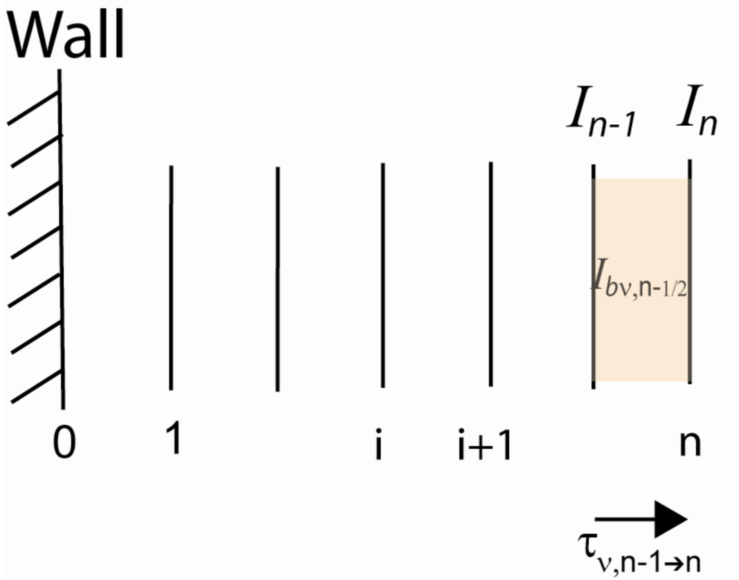
$$I_{\nu,n} = I_{\nu,0}\tau_{\nu,0\to n} + \sum_i I_{b\nu,i+1/2}\left(\tau_{\nu,i+1\to n} - \tau_{\nu,i\to n}\right)$$



Non-correlated formulation

requires less calculations
the most commonly used approach in CFD

$$I_{\nu,n} = I_{\nu,n-1}\tau_{\nu,n-1\to n} + I_{b\nu,n-1/2}\left(1 - \tau_{\nu,n-1\to n}\right)$$

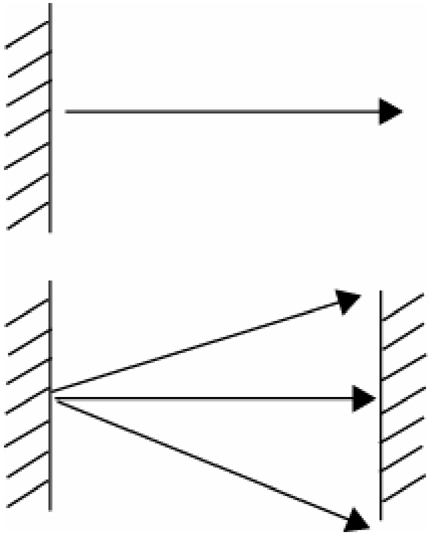


Tested models

	Model	Nr. of RTEs	Ranges of parameter validity
Transmissivity models Correlated formulation	SNBM Malkmus Soufiani and Taine, 1997	367	Cover conditions of interest
	SNBM Goody Leckner, 1972	686	Cover conditions of interest
	EWBM Edwards, 1976	21	Cover conditions of interest
Absorption coefficient models Non-correlated formulation	SLW Denison and Webb, 1993	Optional, 121 are used in this work (10 for each species)	Cover conditions of interest
	WSGG Smith et al.1982	4	$600<T<2400$ $0.001<PL<10$ $P_{H2O}/P_{CO2}=1$ or 2
	WSGG Optimized this work	3 or 4	$500<T<2500$ $0.001<PL<40$ $P_{H2O}/P_{CO2}=0.125$ or 1

Theoretical cases

uniform and non-uniform paths
radiative source term (infinite plates)
wall fluxes (infinite plates)



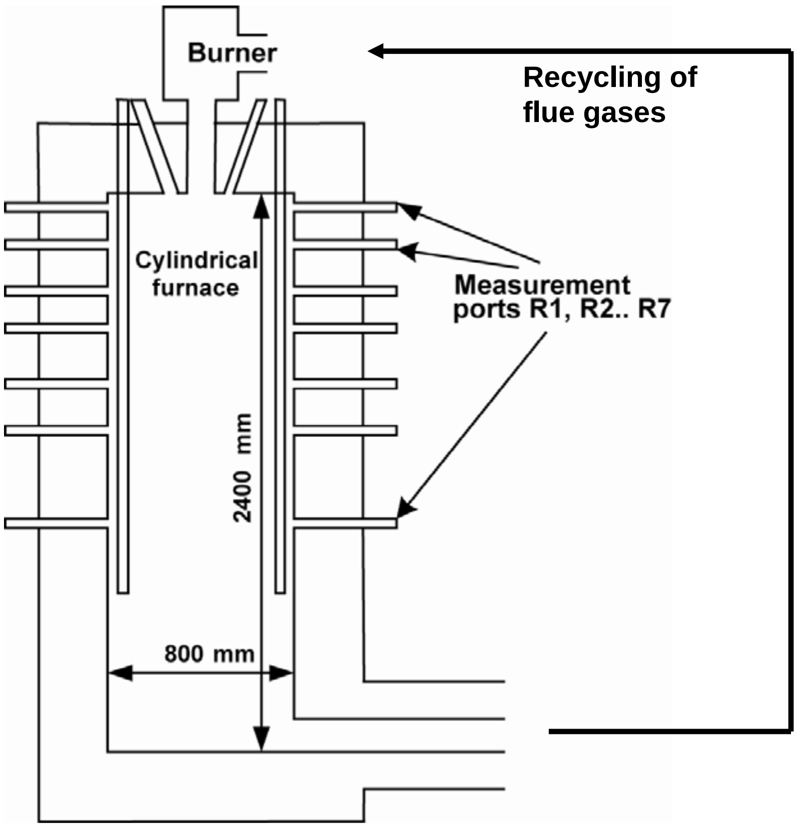
Comparison with experiments

Experimental cases

Fuel	Test case	O_2 [vol.%, dry] In	O_2 [vol.%, dry] Out	CO_2 [vol.%, dry] In	CO_2 [vol.%, dry] Out	Fuel input [kW]	S.R. (λ)
Propane	Air	21	3.0	-	12	80	1.15
	OF 21	21	3.0	77	94	80	1.15
	OF 27	27	3.8	71	94	80	1.15
Lignite	Air	21	3.1	-	17	76	1.18
	OF 25	25	3.7	72	94	76	1.18
	OF 27	27	3.9	71	94	76	1.18
	OF 29	29	4.2	69	94	76	1.18

Measurements

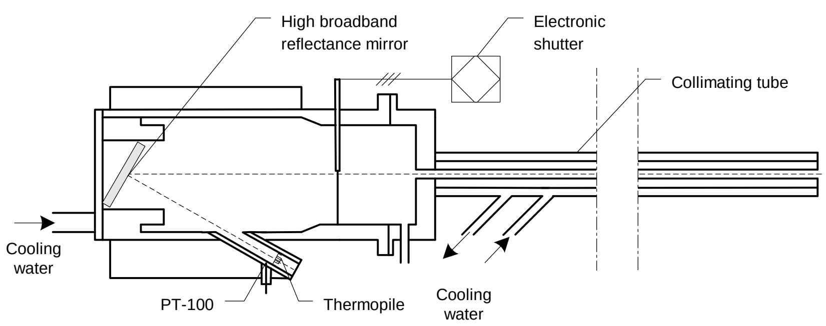
Intensity, temperature and gas concentrations measured along the cross section of several ports.



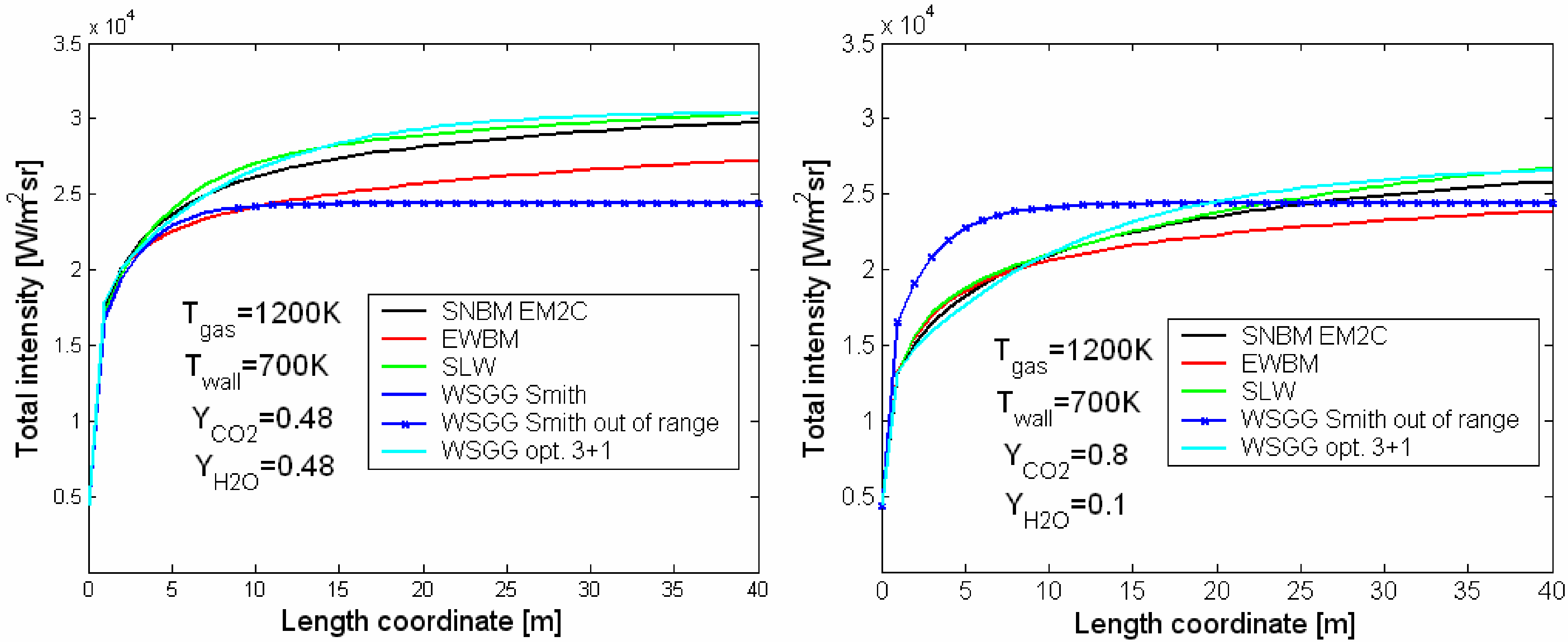
Intensity measurements

Narrow angle radiometer

Cold black background

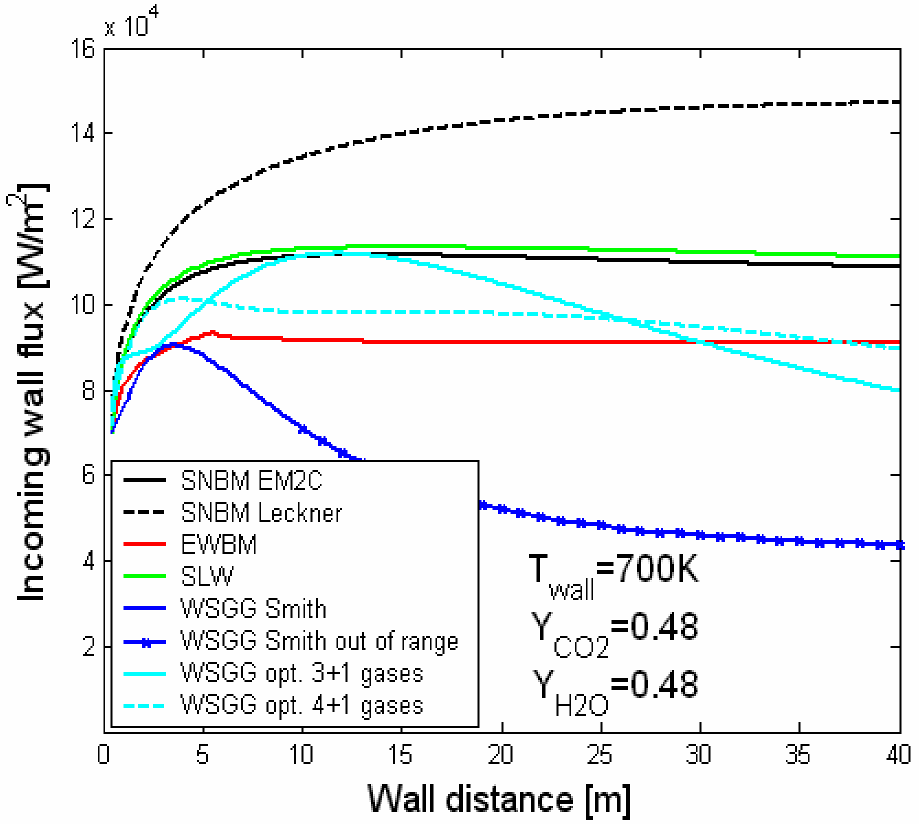


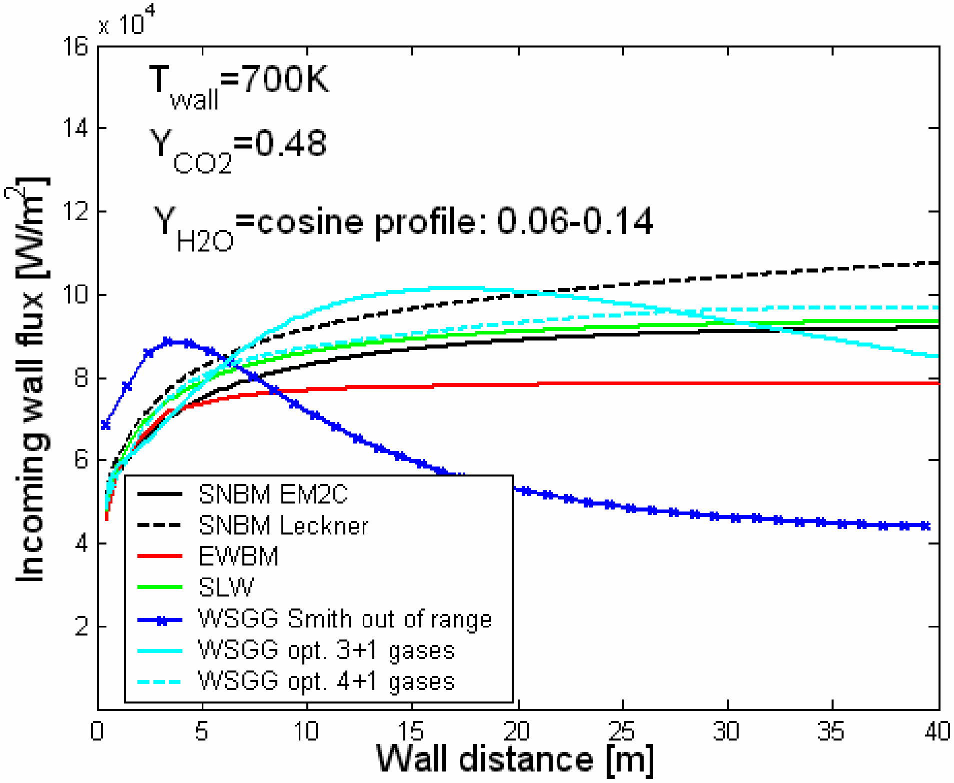
Evaluation of models: uniform paths



Evaluation of models: wall fluxes (infinite plates)

Temperature given by a cosine profile: 1000-1800K

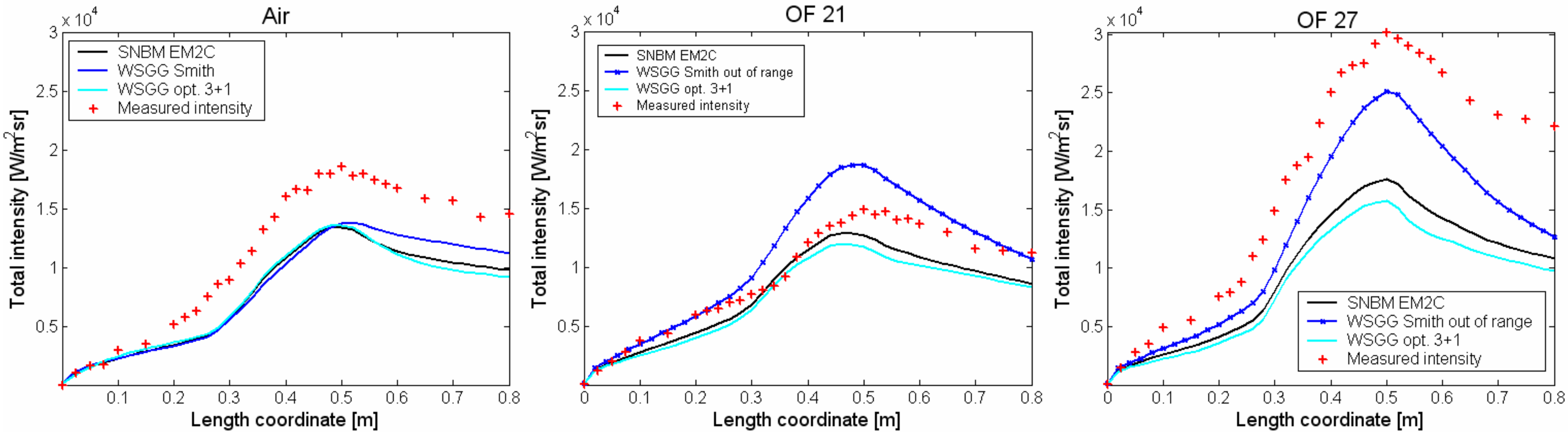




Robert Johansson, Department of Energy and Environment

Comparison with experiments

Propane flame
Port 3: 384mm from burner

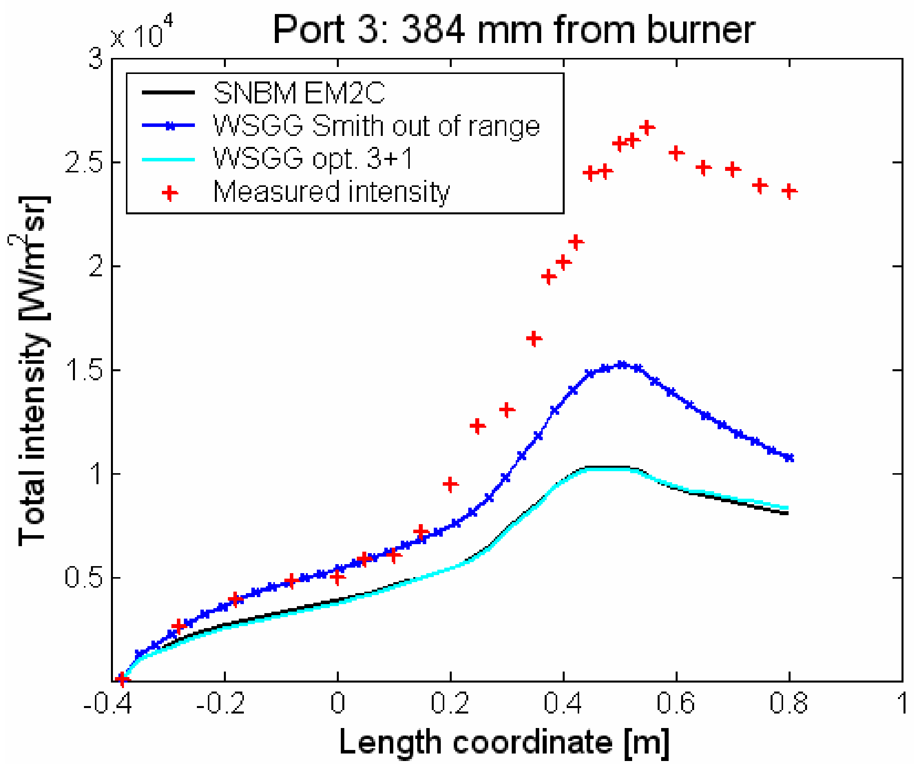


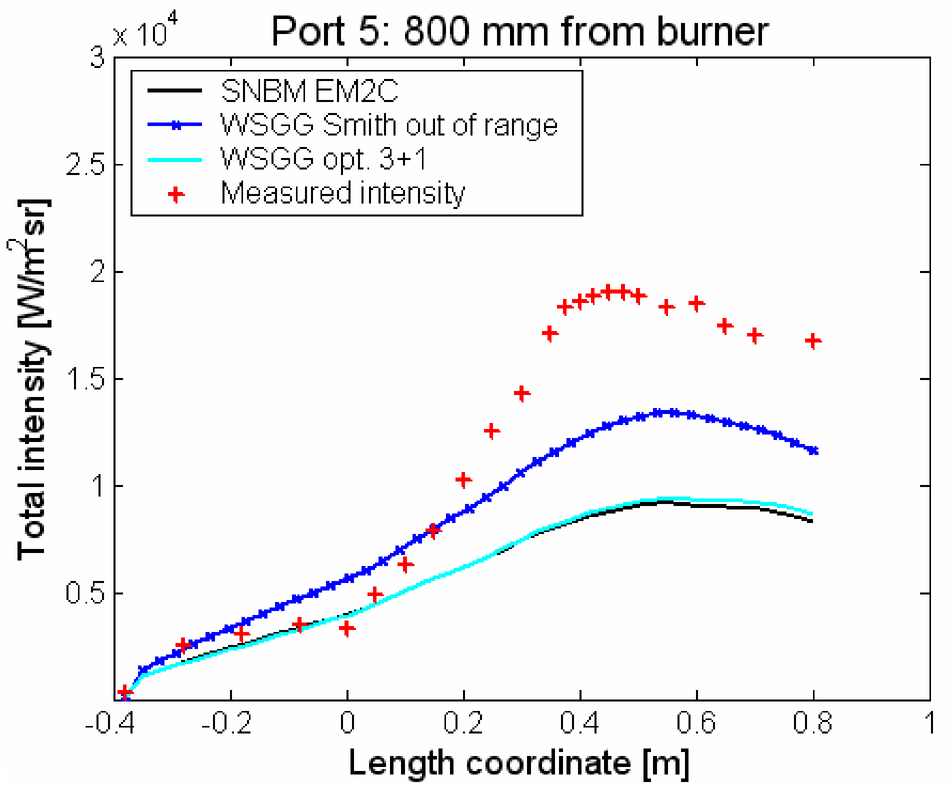
Comparison with experiments

Propane, Air　　Propane, OF 21　　Propane, OF 27

Comparison with experiments

Lignite flame, OF25





Conclusions

- The existing parameters of the WSGG model are intended for air fired conditions and often yield significant errors for conditions relevant for oxy-fired furnaces.
- The new WSGG parameters give results within 20% of the reference model.
- The WSGG model is suitable for CFD-calculations in terms of accuracy and computational cost.
- Conditions with significant amounts of soot and particles requires less accuracy of the gas radiation modeling.
- Modeling has confirmed the differences in soot concentration observed in the propane flames.

Thank you for your attention!

Stabilising Swirl Pulverised Coal Flames under Oxyfuel Conditions

D. Toporov, M. Förster, R. Kneer
Institute of Heat and Mass Transfer, RWTH Aachen University, Germany

3rd Workshop

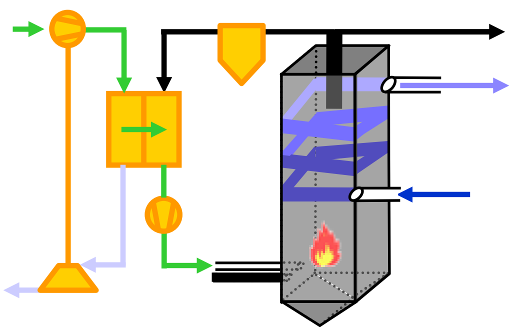
IEAGHG International Oxy-Combustion Network

Yokohama, Japan – 5th and 6th March, 2008

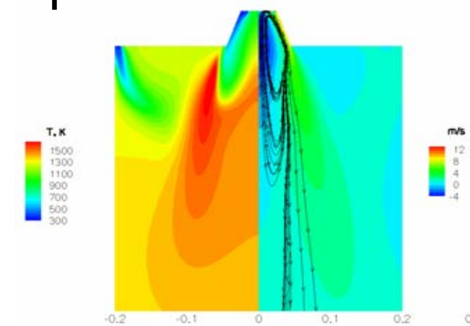
Overview

This talk presents computational analysis and experimental results of swirl flame stability under oxycoal conditions

OXYCOAL-AC Project



Oxycoal Burner Design & Computational Predictions



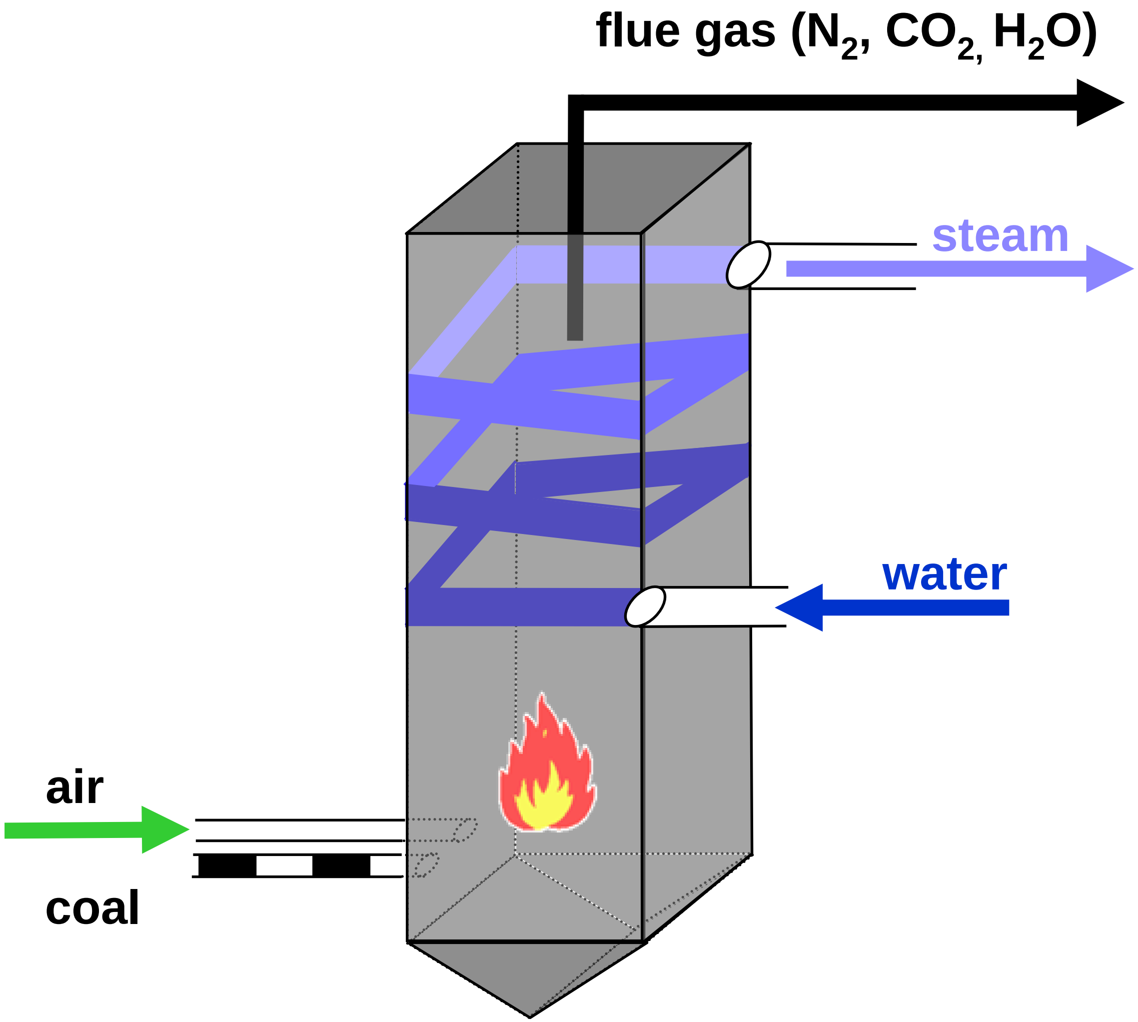
Experimental Set-Up

Experimental Results

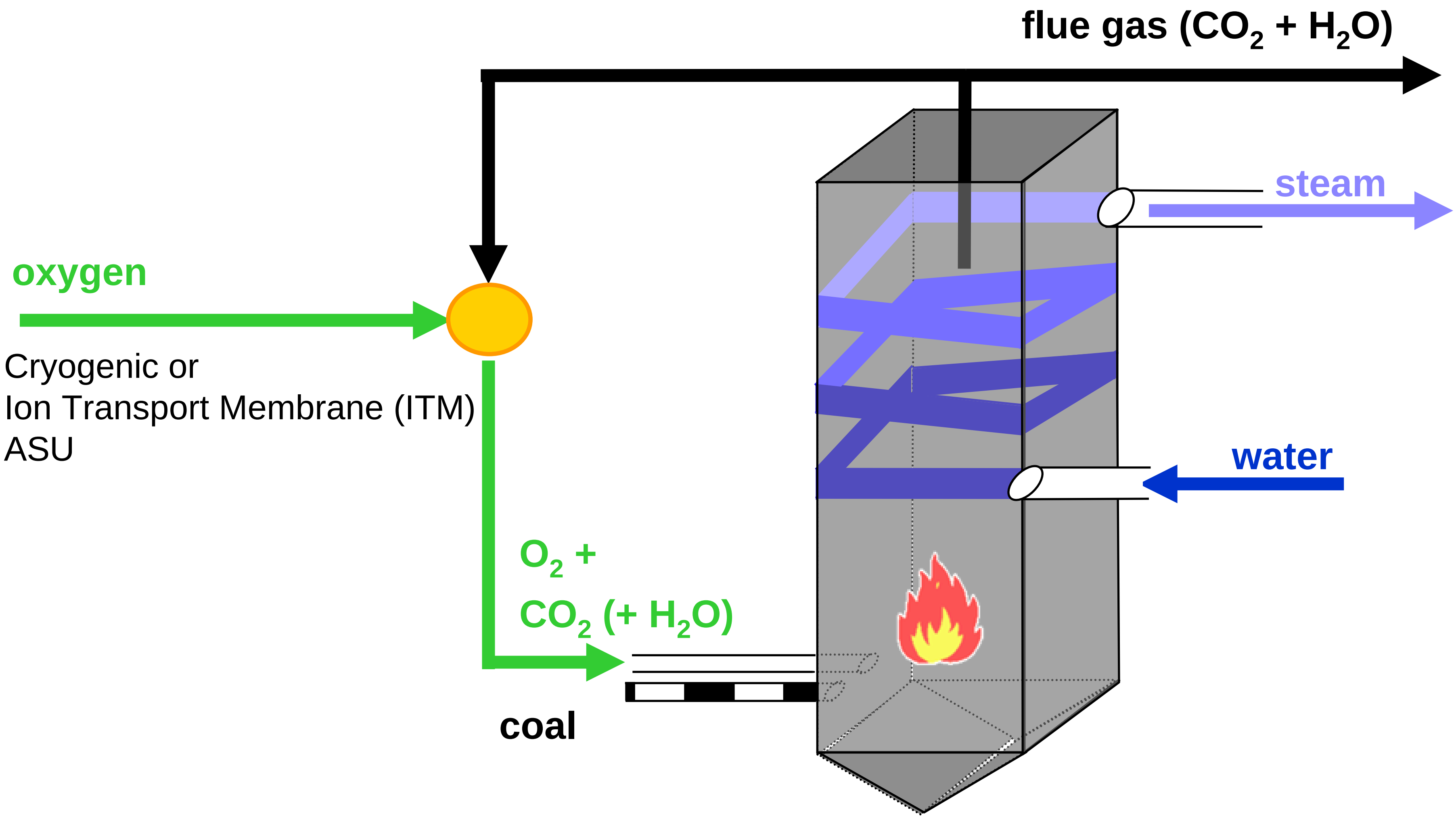
Conventional Power Plant

Block K, 1012MW$_{el}$, net efficiency over 43 %, lignite coal, RWE Power, Niederaussem, Germany

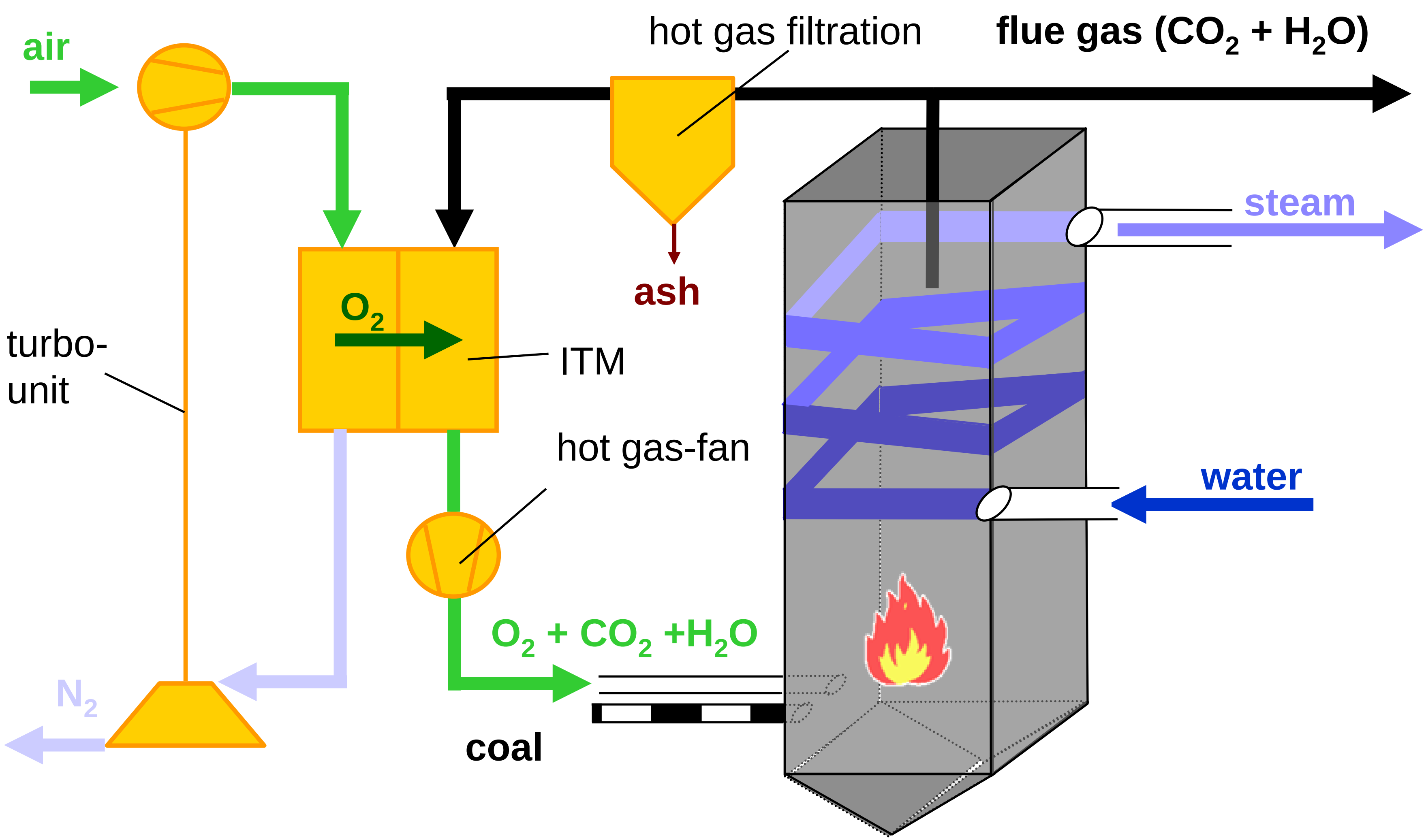
Conventional Steam Generator



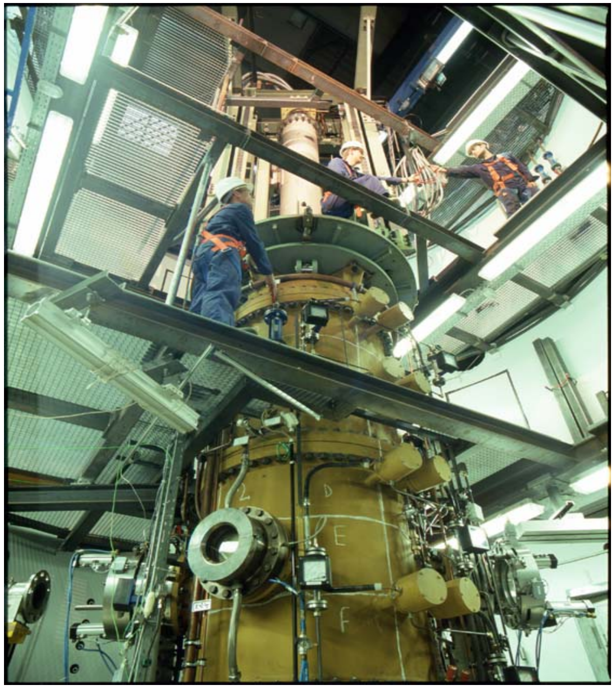
Oxyfuel Process



OXYCOAL - AC Process



Cooperative Research Project OXYCOAL-AC



Goal: Development of a Zero-CO_2-Emission Coal Combustion Process for Power Generation

Topics: Coal Combustion in CO_2/O_2-Atmosphere
High Temperature Membrane for Oxygen Supply

Funded by:

Ministerium für Innovation, Wissenschaft, Forschung und Technologie des Landes Nordrhein-Westfalen NRW.

Bundesministerium für Wirtschaft und Technologie

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WS

HITACHI Inspire the Next

Partners at RWTH AACHEN

WSA – Institute of Heat and Mass Transfer	AVT Aachener Verfahrenstechnik – Dept. of Chemical Engineering
IRT – Institute of Automatic Control	Institute of Jet Propulsion and Turbomachinery
IWM – Institute for Materials Application in Mech. Eng.	ITV – Institute of Combustion Technology

Oxycoal with Ion Transport Membrane (ITM)

Why ITM?

- Cheaper alternative to cryogenic-ASU due to:
  - reduced auxiliary power required

Challenges:

- ITM ←— O_2 % —→ Combustion
- a reduction of the membrane surface area becomes possible by achieving good combustion performance at:
  - near stoichiometric conditions
  - low O_2-concentrations in the CO_2/O_2 mixture

Objective

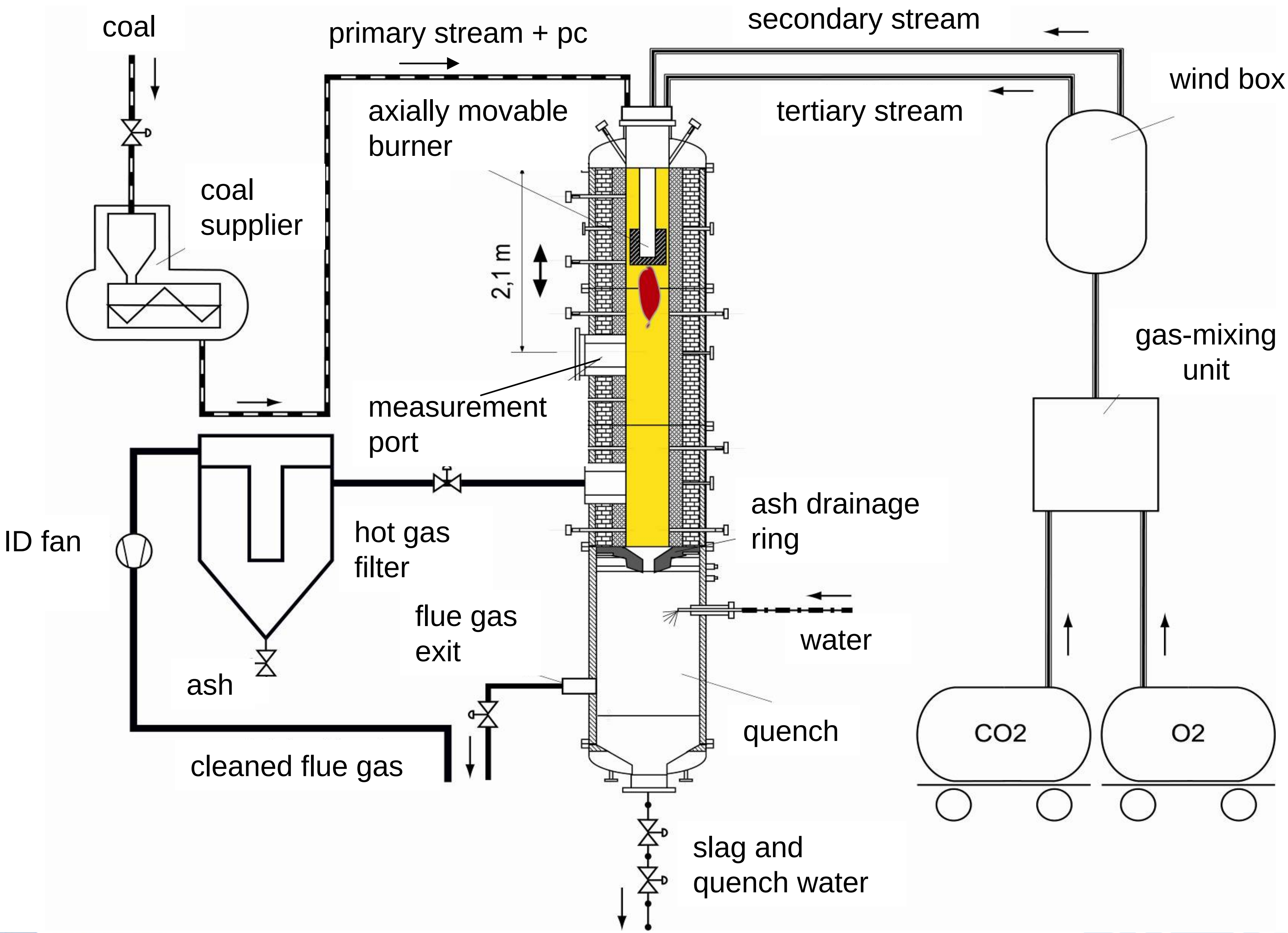
- To obtain stable and controlled oxycoal combustion at low O_2-concentrations in the CO_2/O_2 mixture by identification of
  - the underlying mechanisms
  - the stability limits of an oxycoal swirl flame

Gas Properties for CO_2 Compared to N_2 at 900 °C

- thermal conductivity, k ~ 9 % higher
- molar heat capacity, c_p ~ 67 % higher
- density, ρ ~ 57 % higher
- thermal diffusivity, α ~ 35 % lower
- molecular weight, M ~ 57 % higher
- radiative properties differ significantly

Source: VDI-Wärmeatlas, 2002

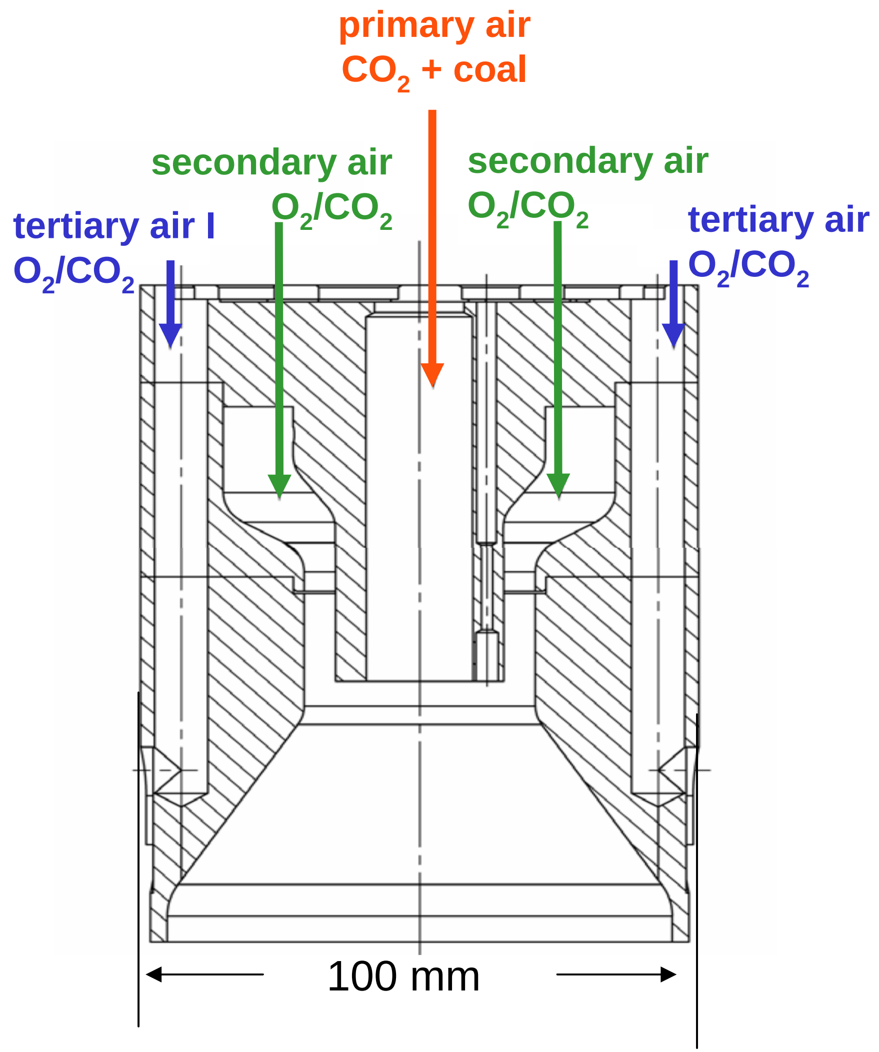
WSA OXYCOAL Test Facility



Burner Development

Base:

- Swirling pulverized coal burner for air operation (burner A)
- Fuel: Rhenish lignite (pre-dried)
  - water: 8.4 %
  - ash: 4.1 %
  - VM: 46.6 %
  - FC: 40.9 %
  - HV: 22173 kJ/kg
- Wall conditions 1200 K
- Inlet temperature
  - PA and SA - 330 K
  - TA II – 900 K
- Lambda 1.3



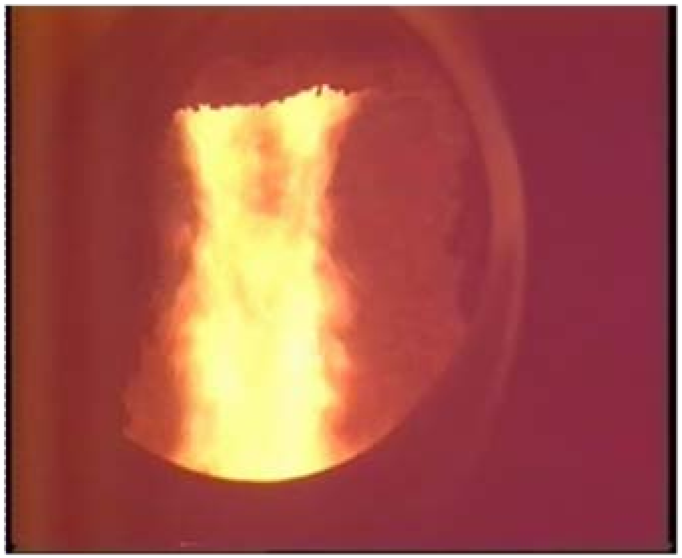
Operation of Burner *A*: AIR and OXYCOAL Mode (80 kW)

AIR Operation:

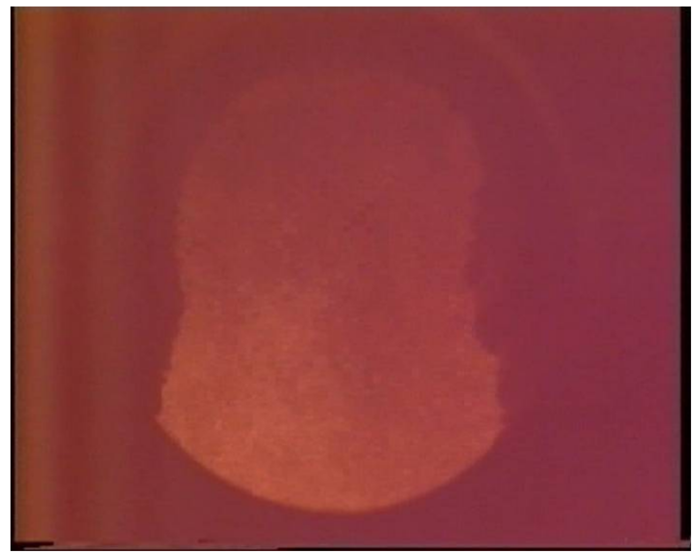
- primary: coal + air;
- secondary: air;
- tertiary: air

OXYCOAL Operation:

- primary: coal + 19% O_2; CO_2
- secondary: 21% O_2; CO_2
- tertiary: 21% O_2; CO_2



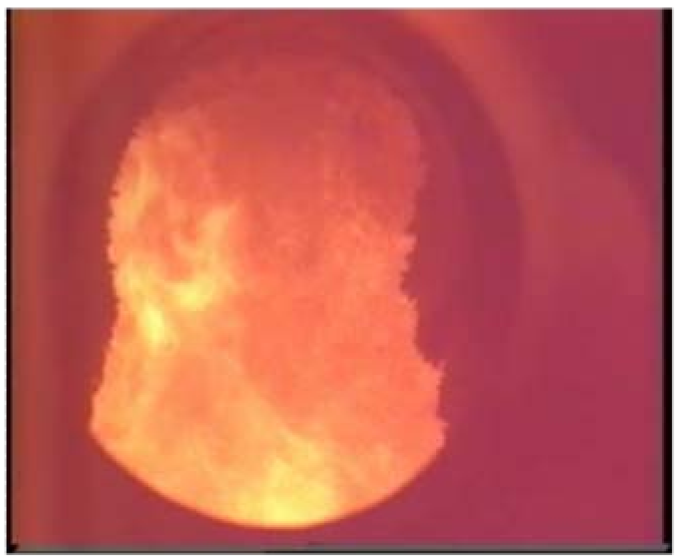
stable flame



unstable combustion

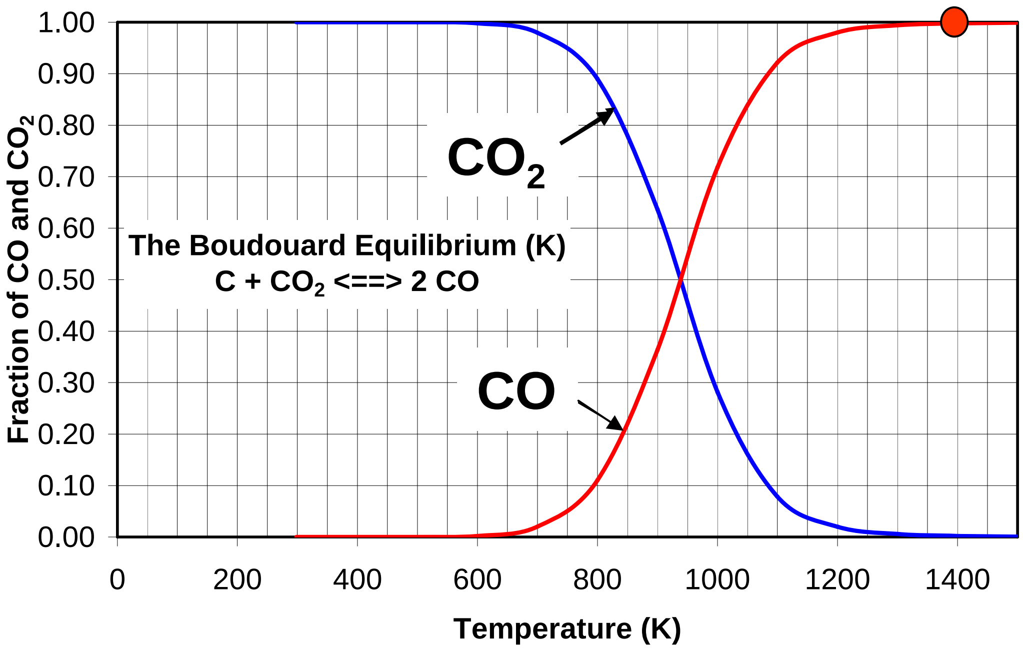
OXYCOAL Tests with Increased O_2 - Levels

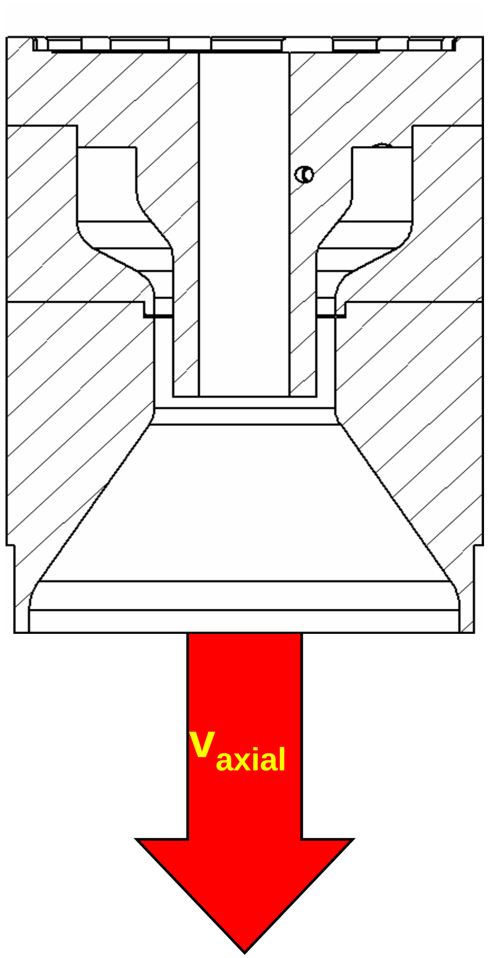
- In order to stabilise the flame at the burner quarl, the thermal load (respectively the velocities at the burner) was decreased to 40 kW
- Results:
  - A stable flame was obtained at the following conditions only:
    - transporting fluid: air | CO_2 + 19 % O_2
    - combusting fluid: CO_2 + 27 % O_2 | CO_2 + 34 % O_2
  - Lower O_2 concentrations in the combusting fluid led to pulsating flame and unstable combustion



pulsating flame (O_2 ~ 30 % vol)

Boudouard Equilibrium





- Endothermic reaction (173 kJ/kmol)
- $CO_2 + C_s \rightarrow 2\ CO$
  $\rightarrow$ Volume doubling (local oscillations)

Consequences with Respect to Burner Design

Phenomena when replacing N_2 by CO_2:

- Increased specific heat capacity: $c_{p,molar}$ $(CO_2) > c_{p,molar}$ (N_2); by ~ 70 %
- CO-production due to Boudouard reaction:
  - volume doubling leads to local flame oscillations
  - endothermic reaction limits the particle temperature rise

Counter-measures:

- Achieving constant velocities at the burner
  - by stabilising the CO-production
- Compensation for higher molar c_p and for the Boudouard reaction
  - by increasing the heat supply to the burner quarl

Solution:

- Increased internal recirculation of hot combustion products

Development of an OXYCOAL - Burner

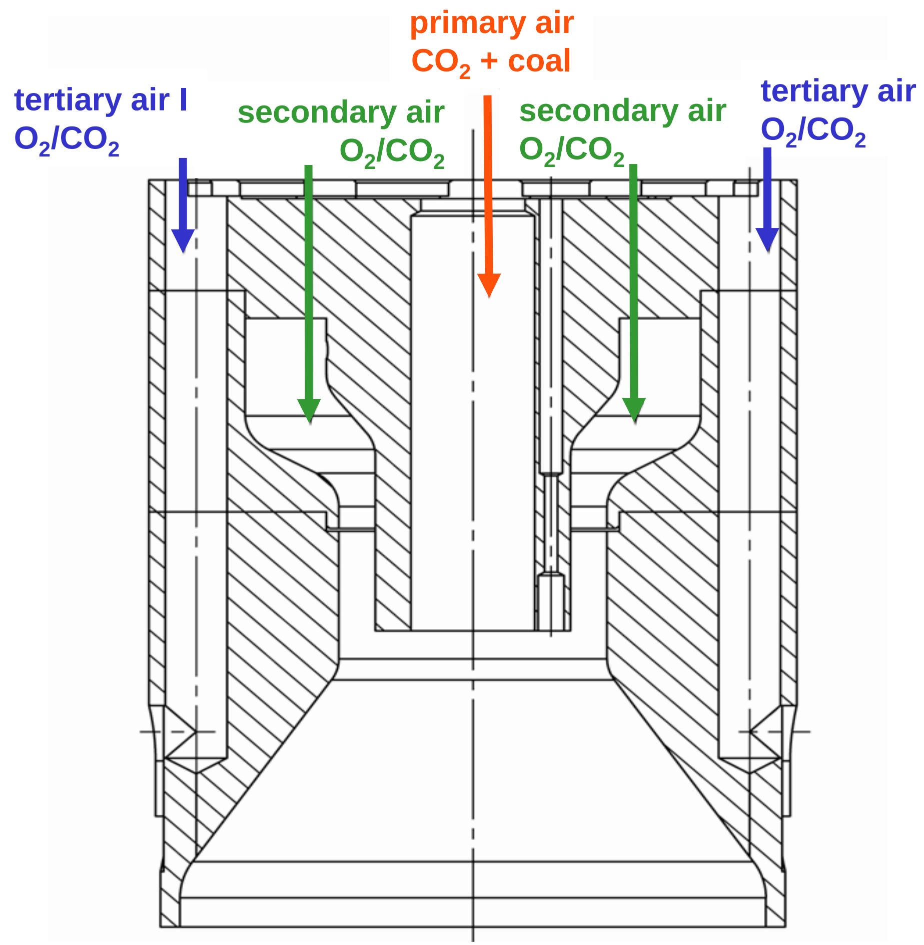
From burner *A* to burner *Oxy-1*

Approach:

- CFD based burner design
  - change of the quarl of burner *A* by removing the parallel ending quarl:
    - increasing the recirculation within the quarl
  - two heterogeneous reactions have to be considered:

→ $C_s + 1/2\ O_2 \rightarrow CO$

→ $C_s + CO_2 \rightarrow 2\ CO$



Development of an OXYCOAL - Burner

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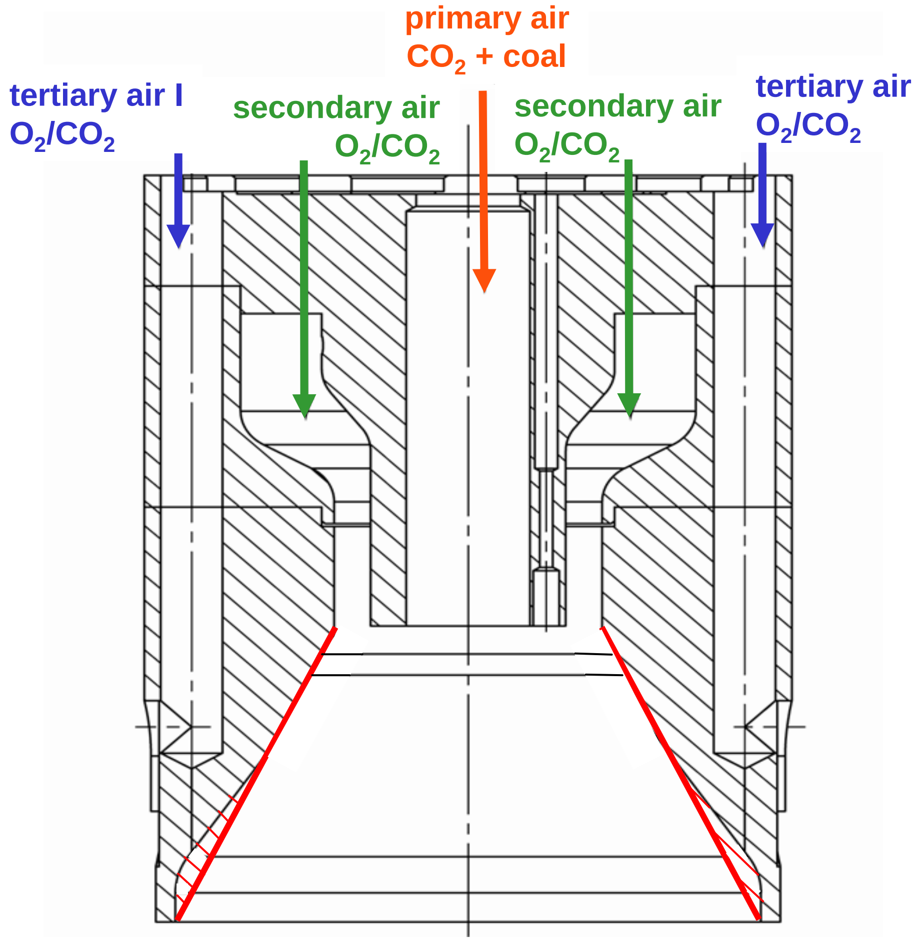
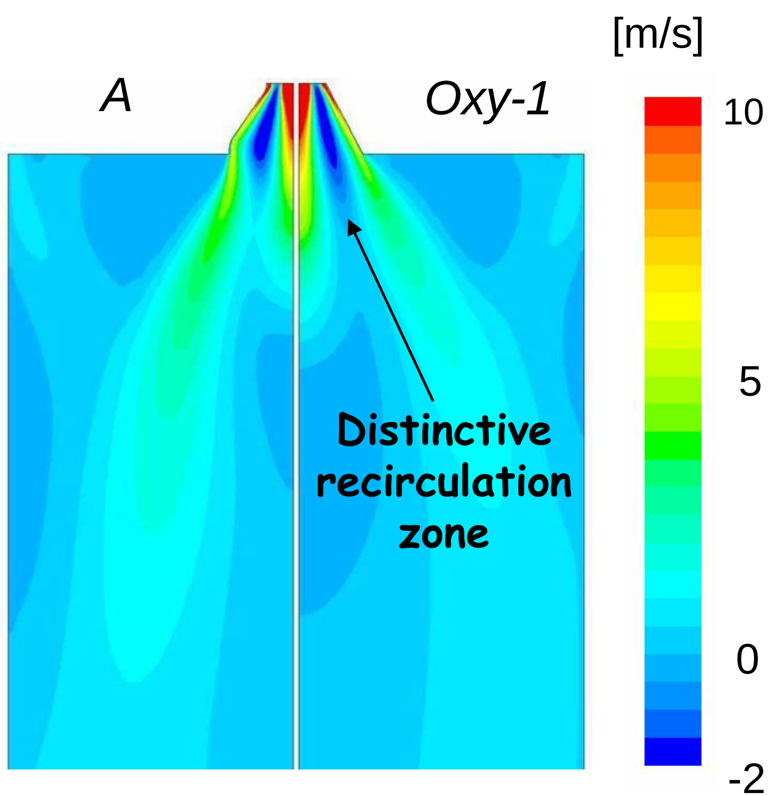
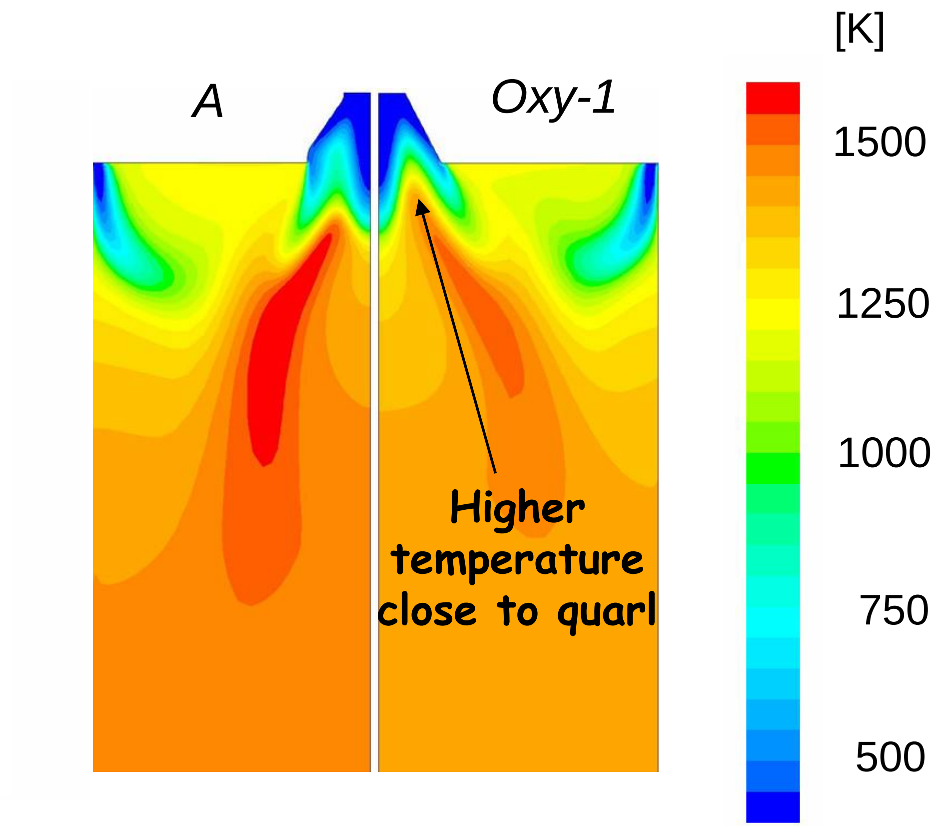


CFD-Simulation: Comparison – Burner *A* vs. Burner *Oxy-1*

Axial Velocity

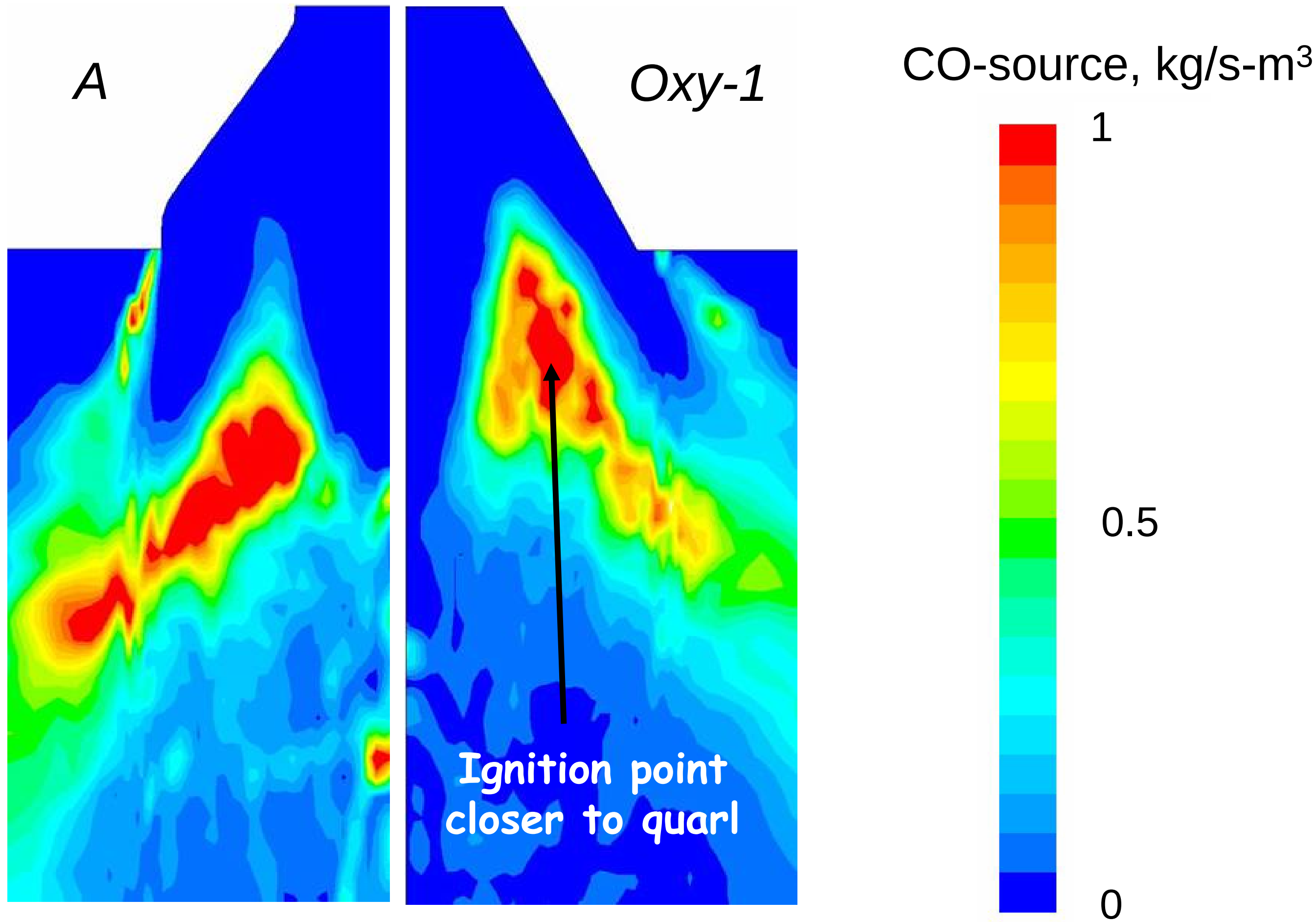


Temperature

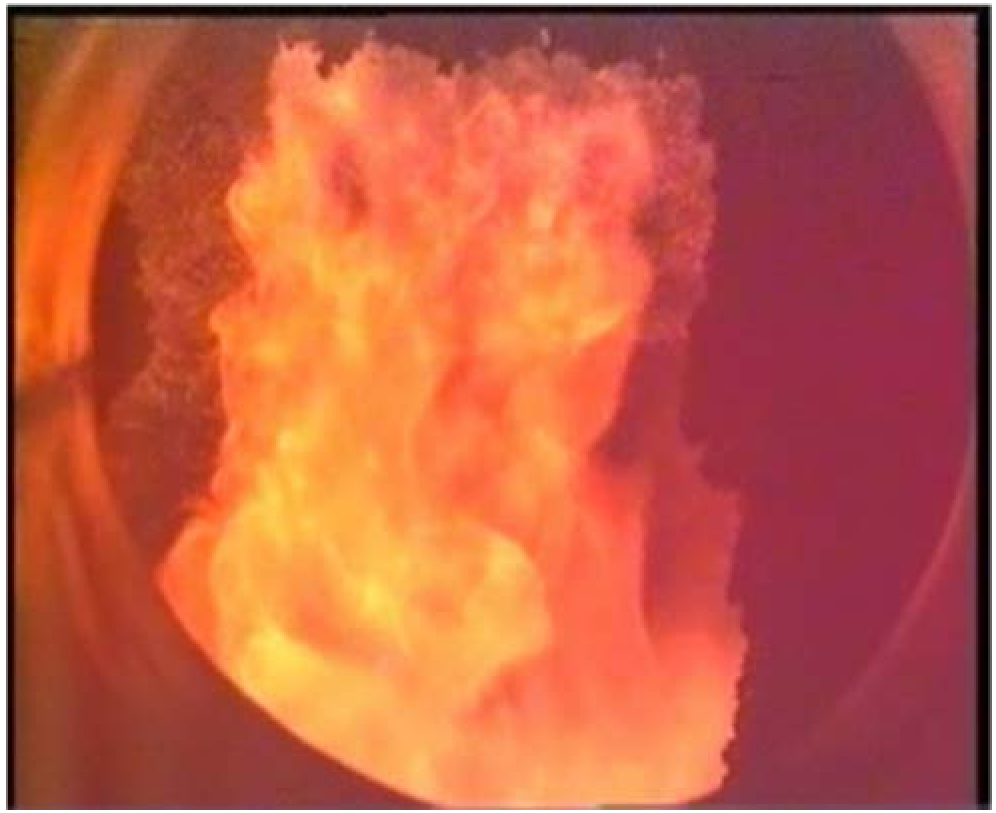


CFD-Simulation: Comparison – Burner *A* vs. Burner *Oxy-1*

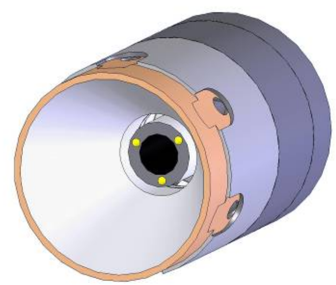
Heterogeneous Reactions



Flame of Burner *Oxy-1*



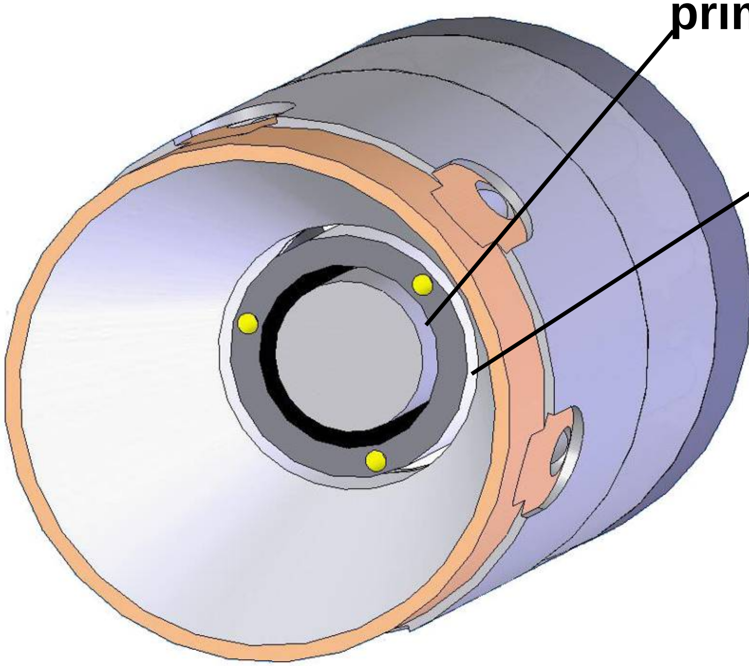
stable flame at ~ 23% O_2



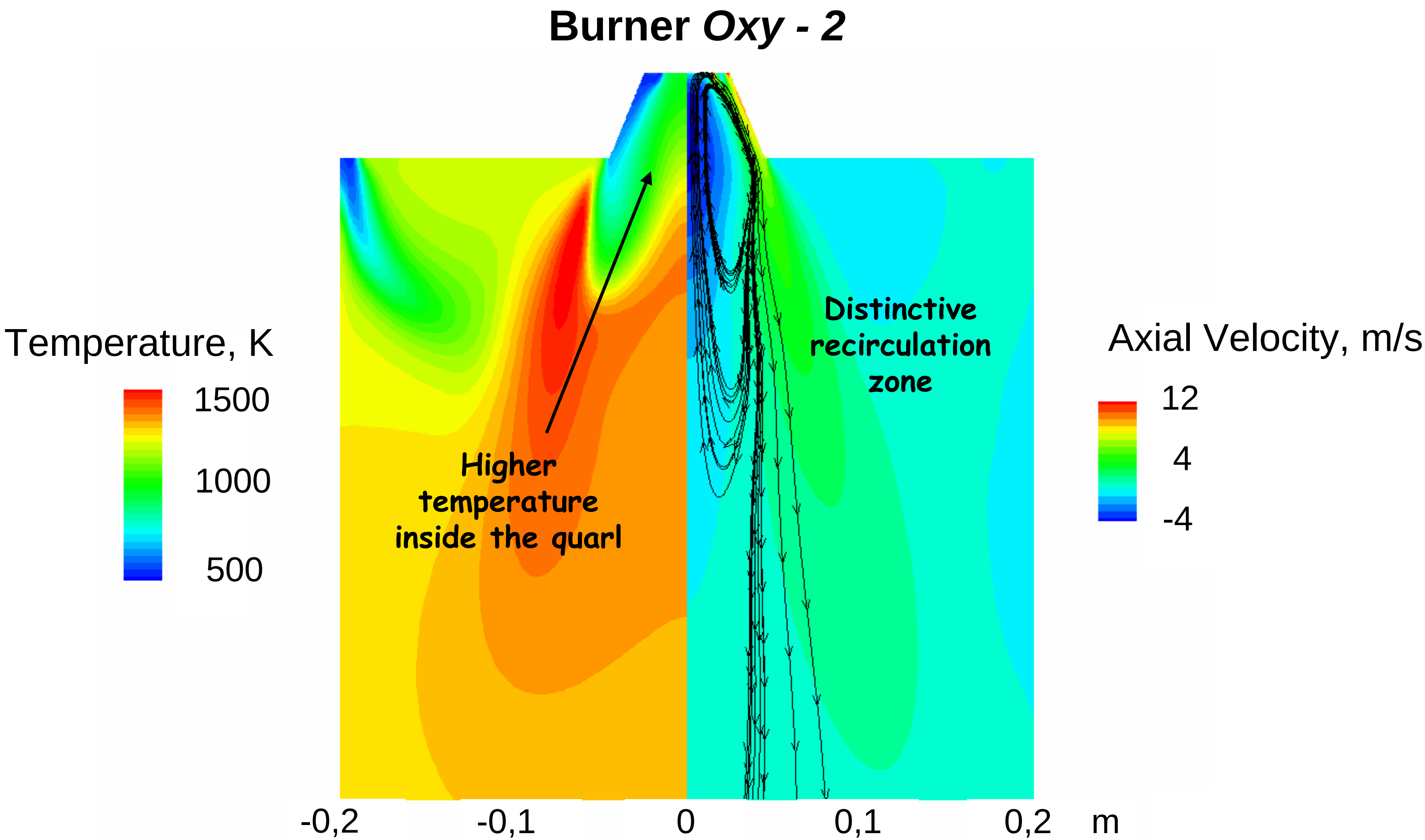
Further Development of the OXYCOAL - Burner

- Experimentally validated CFD simulations → new burner geometry:
  - annular entrance for primary stream and coal (SAO type)
  - increase of internal recirculation yields stable OXYCOAL flame even at O_2 - concentrations around 18 Vol.-% (16 % seems feasible).

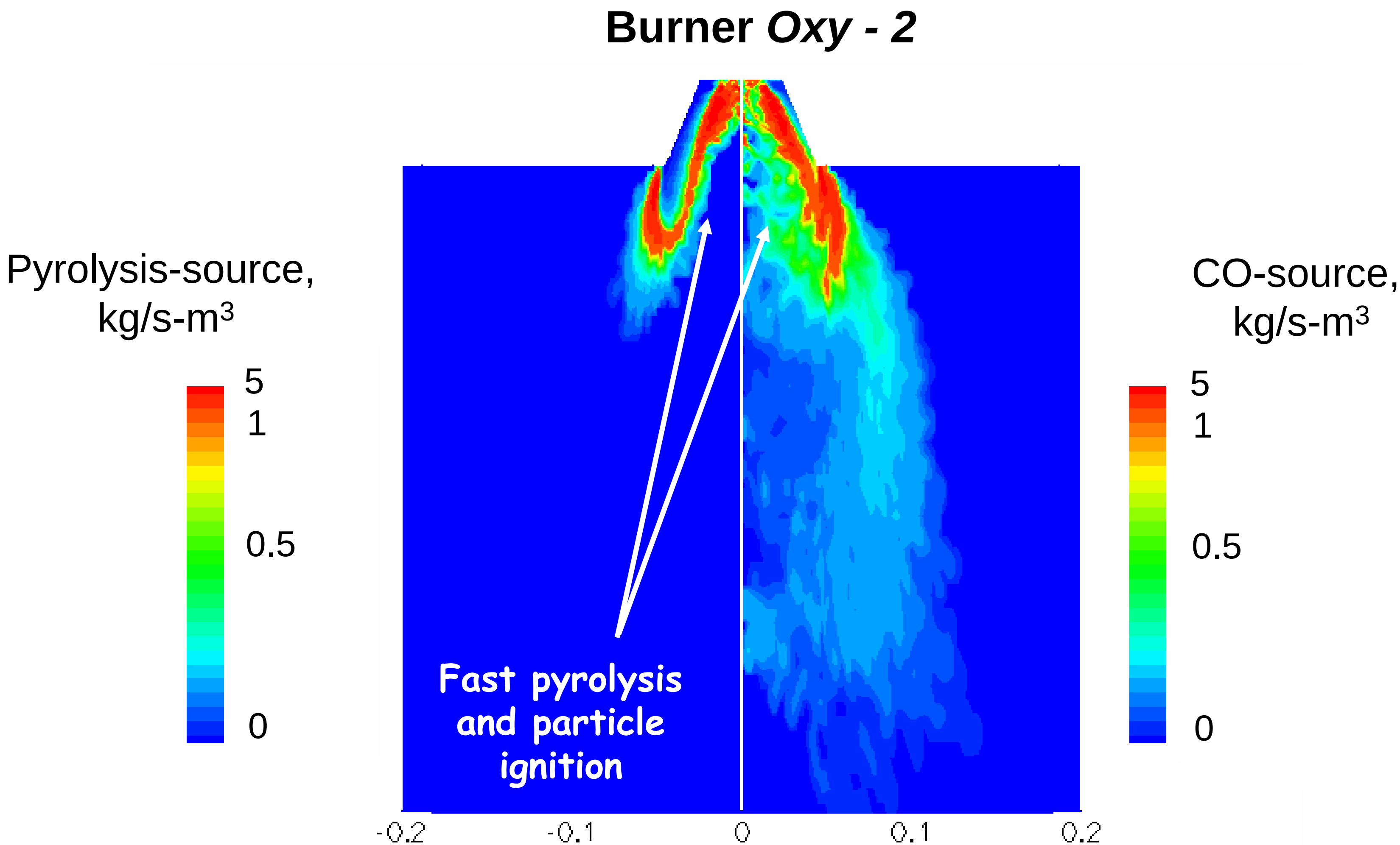
Burner *Oxy-2*



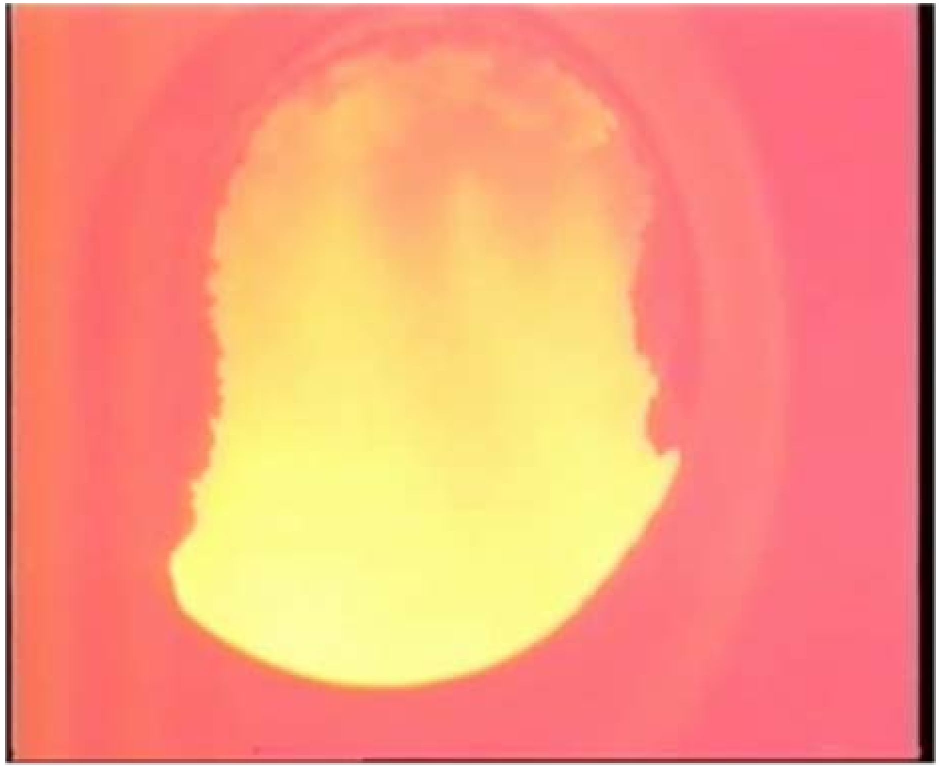
CFD-Simulation: Temperature & Aerodynamics



CFD-Simulation: Volatiles Release and Char Combustion



Flame of Burner *Oxy-2*



stable flame at ~ 21% O_2!

Flames of Burner *Oxy-2*

CO_2 ~ 81%

O_2 ~ 19%

CO_2 ~ 82%

O_2 ~ 18%

Flames of Burner *Oxy-2*

Comparison of Air and OXYCOAL Flames

Air flame	OXYCOAL flame
	
N_2 ~ 79%	CO_2 ~ 79%
O_2 ~ 21%	O_2 ~ 21%

Conclusions

- A stable oxycoal flame with < 18% vol. O_2-concentrations in the CO_2/O_2 mixture was obtained!
  - Development of strong internal recirculation of hot products → an increase of the heat supply to the burner quarl:
    - stable CO-production
    - compensation for:
      - higher heat capacity
      - Boudouard endothermic reaction

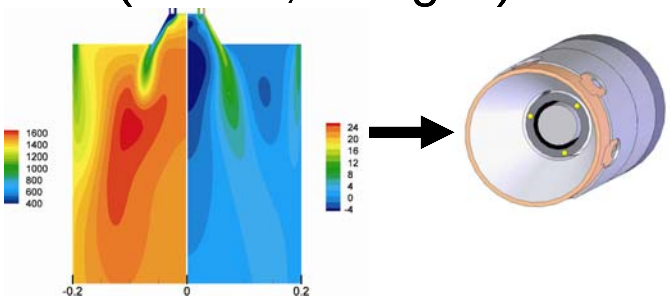
- This achievement opens the possibilities to:
  - an efficient use of ITMs in an OXYCOAL process;
  - a design of industrial burners able to operate in both: *air* and *oxycoal* conditions

- Patent pending - DE 102007021799.6.

Work in Progress

Building-Up of the Complete OXYCOAL Process at RWTH-Aachen

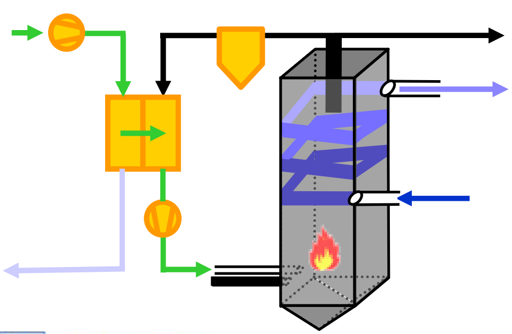
Burner Scale Up 100 kW
(for hot, wet gas)



Implementation of
hot gas filtration

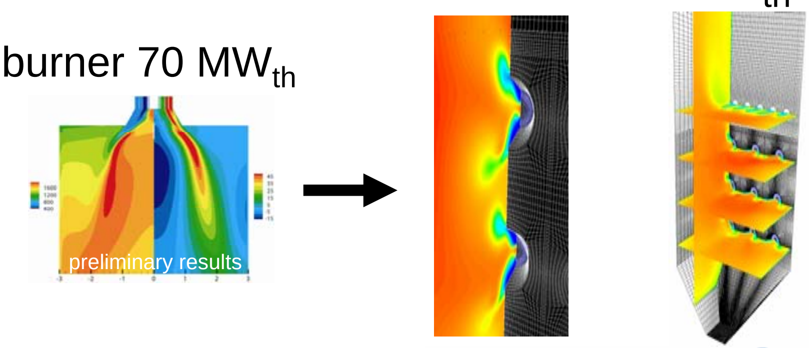
Implementation of
membrane module

Realisation of flue gas
recirculation



CFD based design of full scale oxycoal
burner & furnace - 1210MW$_{th}$

burner 70 MW$_{th}$



Acknowledgments

Industrial Partners:

RWE Power AG

E.ON Energie AG

Siemens AG

Linde AG

WS-Wärmeprozesstechnik GmbH

Partners inside RWTH:

Institute of Heat and Mass Transfer

Institute of Automatic Control

Institute for Materials Application in Mechanical Engineering

Department of Chemical Eng.

Institute of Jet Propulsion and Turbo-machinery

Institute of Combustion Technology

Funding by:

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Institute of Heat and Mass Transfer

RWTH AACHEN

Thank you !

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(arigatou gozaimashita)

MODEL VALIDATION STUDIES FOR PULVERIZED COAL JET IGNITION IN O_2/CO_2 ENVIRONMENTS.

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Jost O.L. Wendt, Philip J. Smith
University of Utah

Presented at
3rd IEA GHG International Oxy-Combustion Network
Workshop, Yokohama,
Japan March 5-6, 2008.

Motivation for this study

- Enabling technology for retrofit in new, efficient, but initially planned as air-fired units that were proven for air firing.
- Short term applications where oxy-coal process still resembles a current boiler configuration.
- Main motivation for this study is to provide data to allow validation of a coal jet ignition sub-model.
- Sub-model to be used in simulations for extrapolation from air fired to oxy-combustion conditions

Retrofit issues: need for *validated* sub-models to <u>extrapolate</u> from air to O_2

- Heat transfer sub-model
  - Radiant zone
  - Convection zone
- Coal jet ignition sub-model ← This work
  - Chemistry
  - Burner aerodynamics and heat transfer
- Char burnout sub-model
- Ash partitioning sub-model
  - Deposition
  - Trace metals
- Combustion by-products
  - NO_x, SO_x, Hg
- Integrated furnace model
  - Calculation of heat transfer, species, temperature profiles in all furnace zones as function of recycle ratio. For heat transfer see *Payne, Chen, Wolsky, and Richter Combust. Sci. Technol, 67,1,1989*

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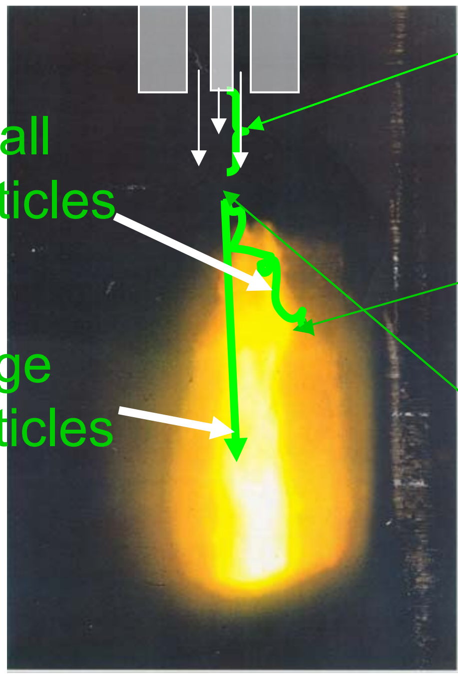
Scope of this research

- Experimental data for validation of model simulations to be used for extrapolation to oxy-coal combustion conditions.
- Focus on turbulent coal jet ignition
  - Effects of P_{O2} in
    - Primary fuel jet
    - Secondary oxidant flow
  - Type 0 axial turbulent diffusion flames
  - Systematic experimentation and controlled conditions
    - Controlled wall temperatures
    - Independent control of velocities and moments through introduction of sleeves.
- Companion program on simulation
  - Development of LES particle flow model to capture previously observed physical phenomena related to particle/eddy interactions..

Coal jet ignition sub-model



•Standoff ignition distance depends on primary jet velocities, and P_{O2}, which becomes an independent variable under oxy-coal combustion

•Sub-model should capture observations that smaller particles preferentially migrate to jet edge. *Sinclair Curtis (2003)*. Implications on effects of secondary P_{O2}, also an independent variable.

•Pyrolysis behavior. *(Naredi and Pisupati, 2007, Penn State University)*

•Particle ignition. (*Shaddix and Molina, 2005, 2006, Sandia Labs)* Influence of gas properties which vary heat transfer to coal particle.

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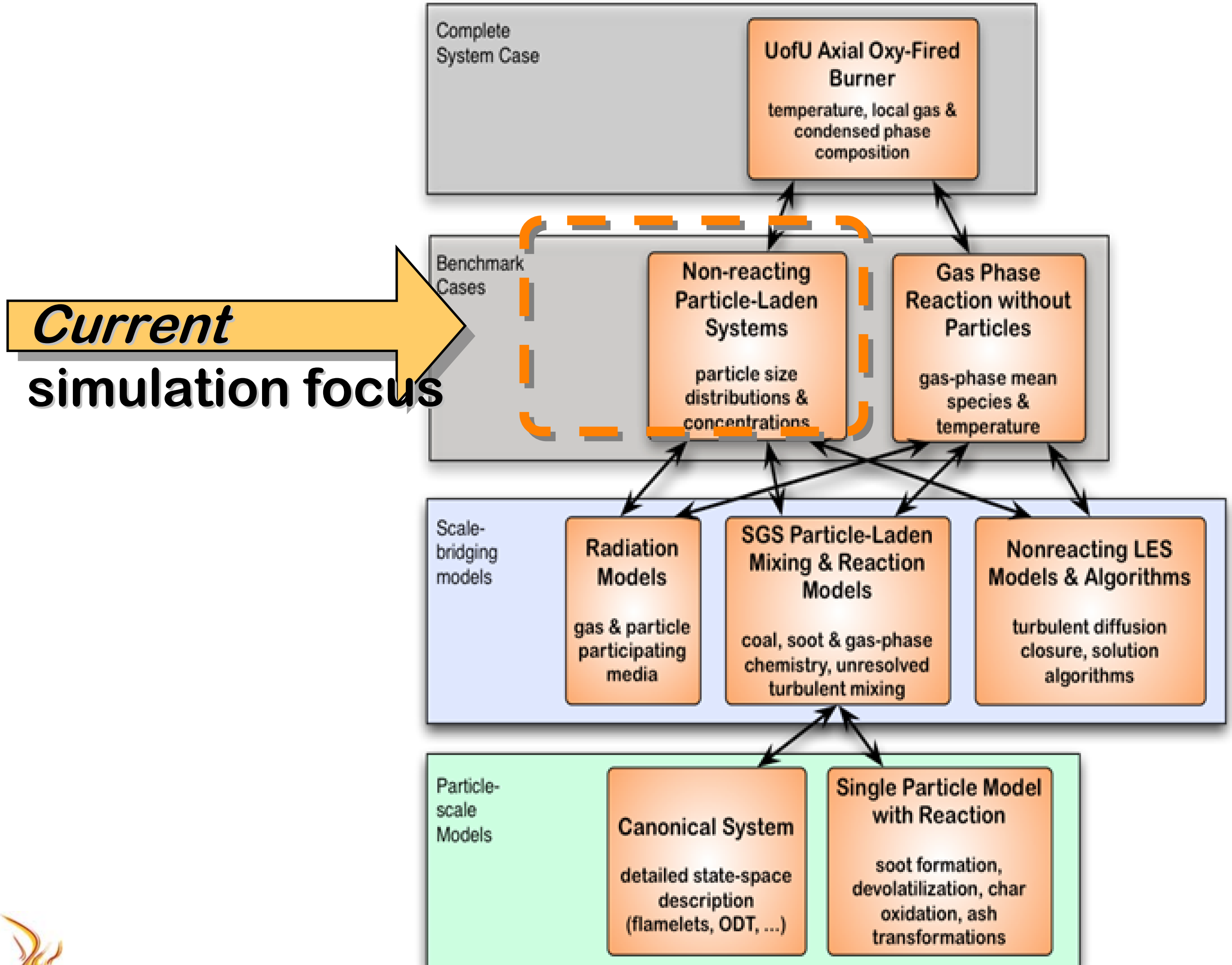
Simulation: validation hierarchy



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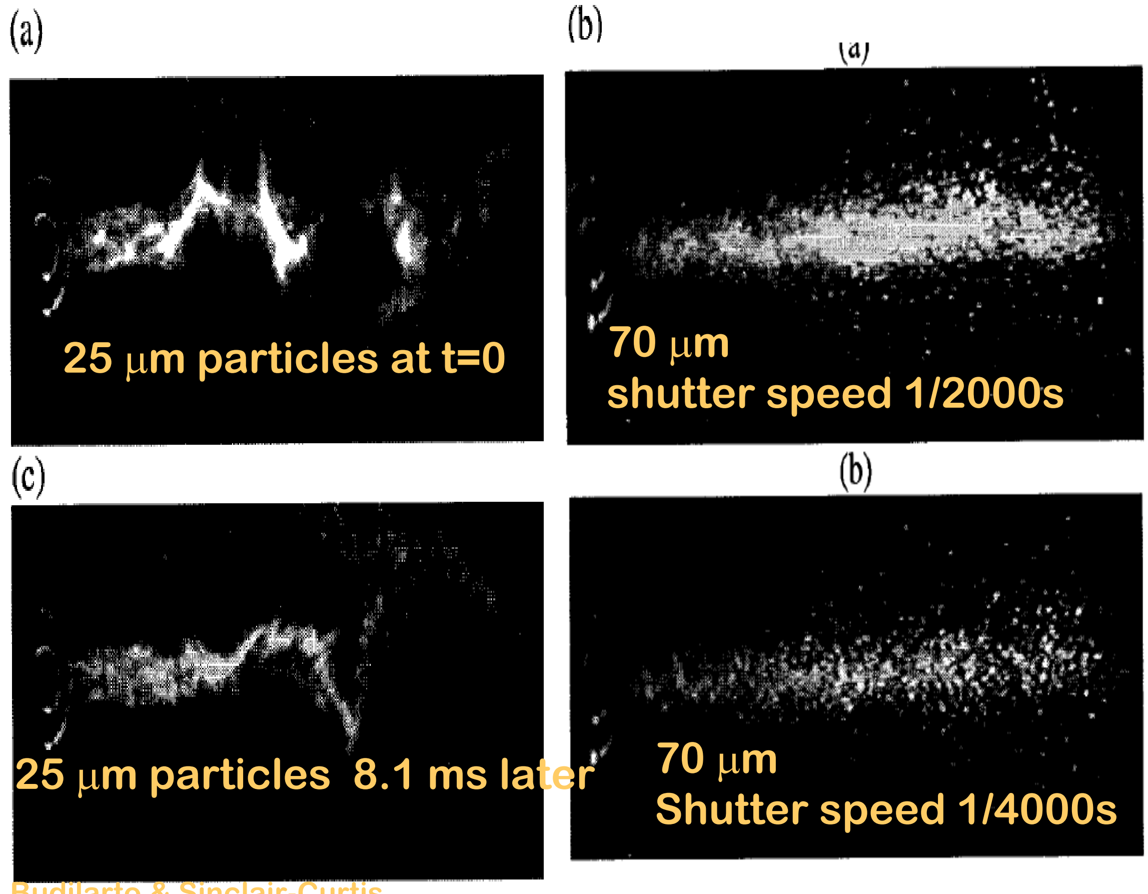
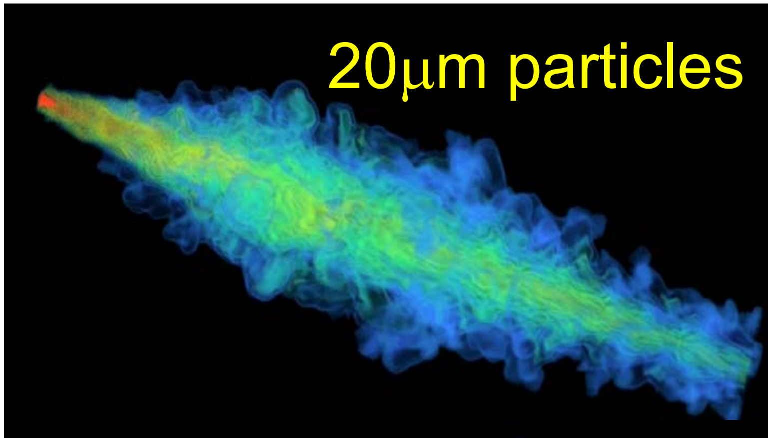
Experimental data: particle laden axial jet – LDV, cold flow.

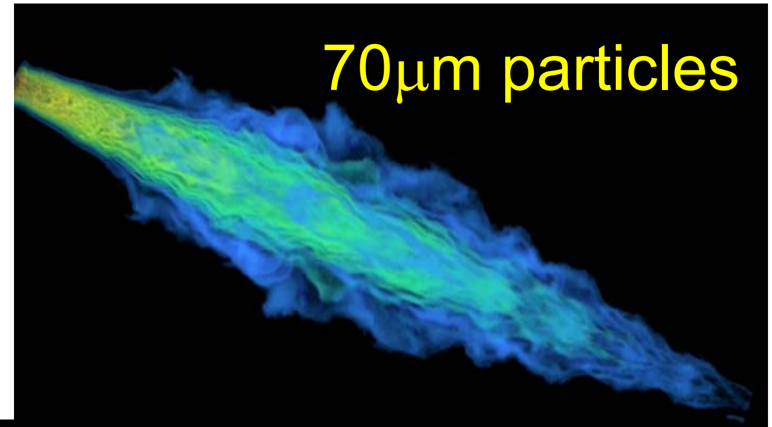
(Budilarto and Sinclair-Curtis, 2003, Purdue U)

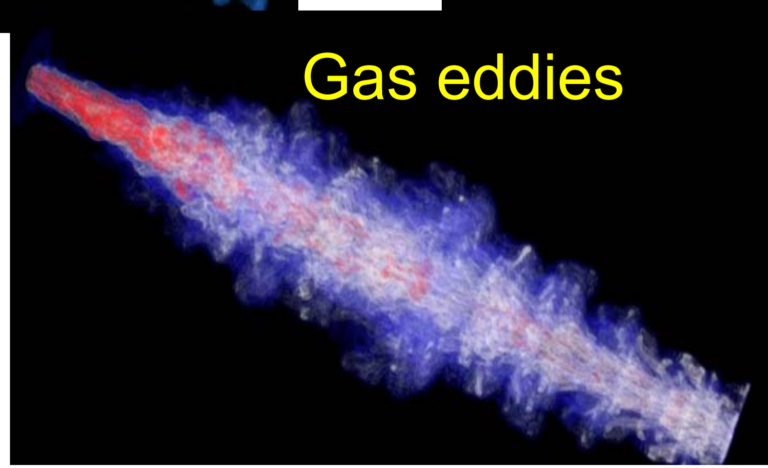


Smaller particles migrate to outside of jet, and follow eddies. Important for particle ignition. Must be captured by simulaton.

Simulation approach # 2: Large Eddy Simulation (LES): particle size effects







Result: LES simulation captures particle/eddy interactions and particle segregation effects.

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Experimental work (in progress)

- Determine, in a systematic manner, how burner operating parameters and oxygen partial pressure influence flame attachment/detachment and coal ignition.
- Systematic investigation of near-burner aerodynamics and ignition zone for *Type 0 axial* diffusion flames (no swirl)
- Use a mixture of O_2/CO_2 to replace either or both primary and secondary air
- Produce data on flame detachment and flame length for simulation validation studies

Design and construction of UU Oxy-Fuel Combustor (OFC).

- Up to 100 kW, down-fired, oxy-coal combustion furnace.
- O_2 and CO_2 supply and delivery infrastructure donated by Praxair C.
- Wall temperature controlled through electrically heated walls.
- Quartz windows for optical access to permit flame detachment/attachment studies and future optical diagnostics.
- Simulate the environments experienced by pulverized coal jet flames in boilers.
- Systematic control of burner momentum and velocity variables, and wall temperatures.

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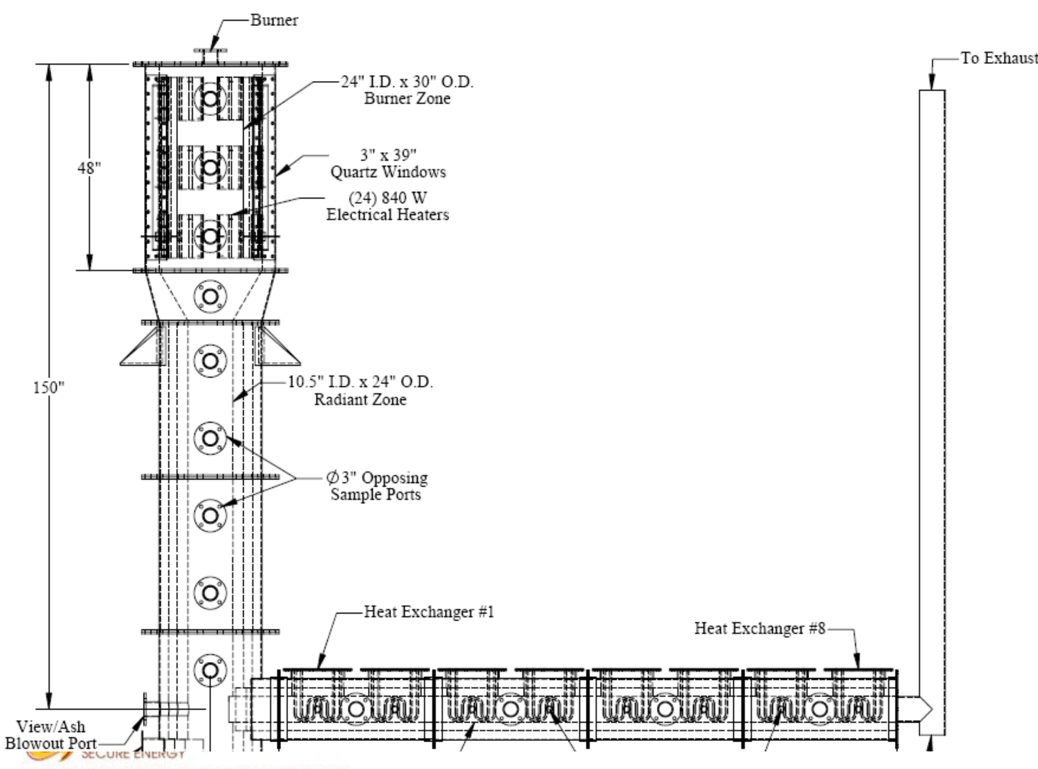
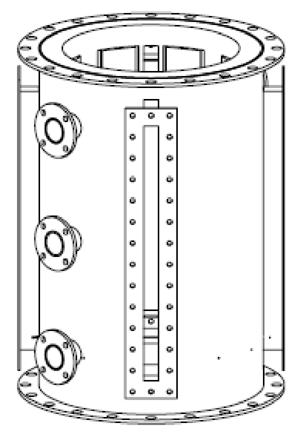
Design details

- Top section: 0.610 m I.D., 0.914 m O.D., 1.219 in height; 2600 Fiberboard (δ = 76 mm)
- 24 × 840 W flanged ceramic plate heaters with k thermocouples controlling or monitoring the temperature
- 3 layers of insulation in radiant zone and 2 layers insulation in convection zone
- 8 heater exchangers to cool down flue gas
- A preheater (640K)





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Preliminary data on “Oxy Enhanced” pc combustion- report of work in progress

- Praxair O_2, CO_2 tanks and delivery train under construction
- Primary air: pulverized coal + air
- Secondary air: air + O_2, O_2 concentrations vary 21% - 30%
- Current data
  - Flame length = f (P_{O2} in sec. air)
  - Temperature profiles and NO, CO, and O_2 flue gas concentrations versus air+coal combustion
  - O_2 enrichment in secondary air can attach flame and lower NO_x (not new).

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Photographic records of flame lengths

- $SR = 1.15 = 0.15_{\text{pri. air}} + 1.00_{\text{sec. air}}$
- Coal feeding rate = 1.95 kg/hr
- $T_{walls} = 1361$ K
- $T_{preheater} = 589$ K
- Primary air: 9.14 m/s
- Utah Bituminous Coal
- Only change P_{O2} in secondary air

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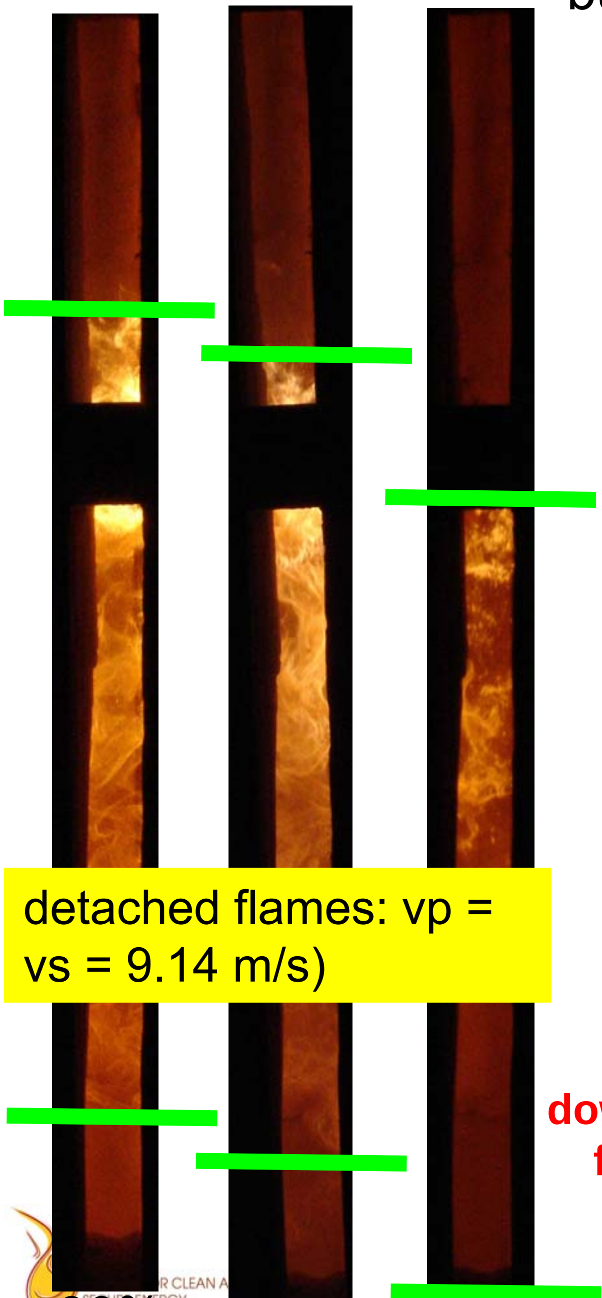
Enriched secondary air: The effect of p_{O2} on flame length

1) P_{O2} ↑ , L_{flame} ↓
2) P_{O2} ↑ , ignition point ↑
3) P_{O2} ↑ , detached → attached

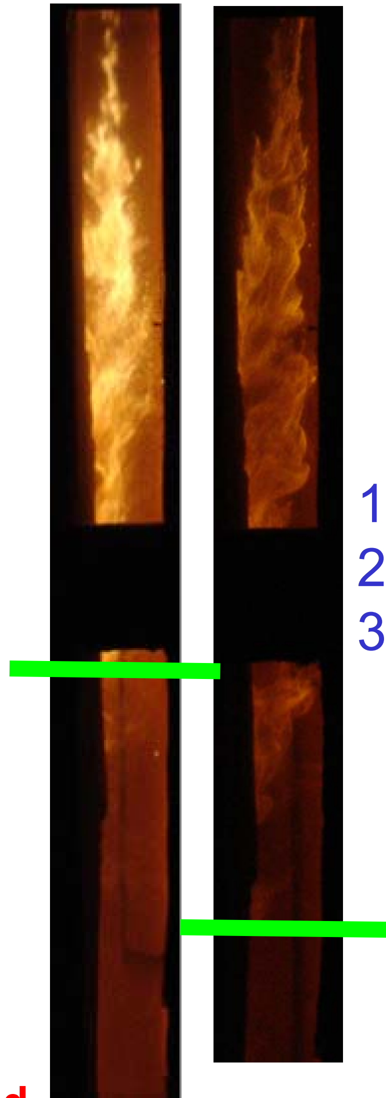
burner



30% 24% air

detached flames: vp = vs = 9.14 m/s)

downfired flame



30% air

Attached flames: vp = vs = 4.57 m/s)

% denotes percentage O_2 is secondary oxidant flow. Primary flow is air (21% O_2)

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Future work

- Solve current experimental challenges
  - Diminish coal feeding rate fluctuations
  - Shorten flame so that it can be viewed in its entirety through existing quartz window
  - Quantify photographic measurement techniques for flame shape and length
- Effects of systematic variations of
  - p_{O2} in secondary flow vs flame length
  - primary air velocity
  - p_{O2} in primary air
  - secondary air velocity
- Effect of wall temperatures
- Effect of preheating temperatures
- Use CO_2+O_2 to replace air+O_2
- Effects of coal composition
- Model validation with simulation group.

Acknowledgments

- US Department of Energy (DOE) funding through Utah Clean Coal Center (UC^3)
- Praxair for (soon to be available) O_2 and CO_2 supply
- University of Utah
- Ryan Okerlund, Brian Nelson, David Wagner, Dallin Call

UK

E.ON UK's Pilot Scale Oxyfuel Combustion Experiences: Development, Testing and Modelling

Ben Goh, E.ON UK

3rd Workshop of the IEA GHG Oxy-Combustion Network
5th and 6th March 2008, Yokohama

Overview

- E.ON and E.ON Engineering
- The 1 MW_{th} Combustion Test Facility
- "ASSOCOGS" (RFCS)
- Conversion of the CTF and operating range
- "OxyCoal-UK" (BERR)
- Results
  - Operation, combustion and heat transfer, emissions, ash behaviour, corrosion, modelling
- Conclusions and plans for the future

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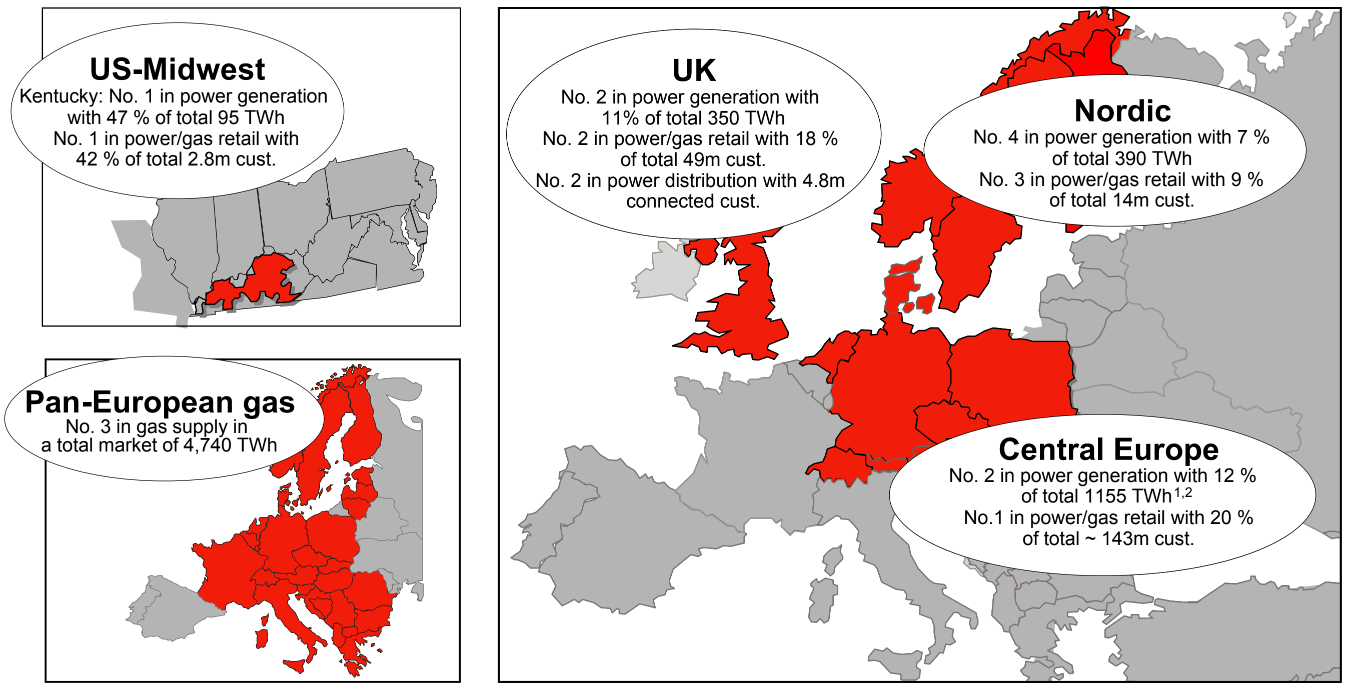
Group Structure

E.ON overview

- Europe's largest investor-owned energy service provider with more than €56bn in sales and operating profit of €7.4bn

Power and gas focus in five core markets with strong positions



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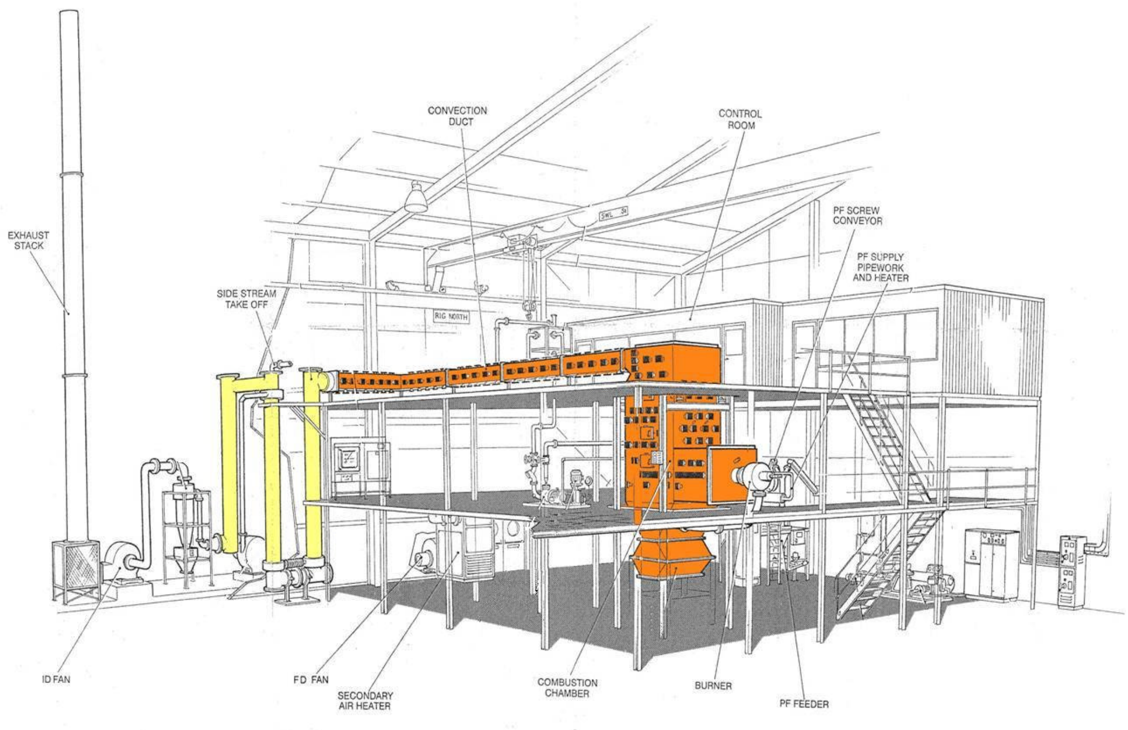
E.ON UK's 1 MW_{th} Combustion Test Facility (CTF)



- Commissioned 1993
- Located in UK
- Time-temperature scaled
- Fuel flexible
  - Coal, biomass, oil, Orimulsion, gas, others
- Full combustion staging
  - Overfire air
  - Reburn
  - Flue gas recycle
- Highly instrumented and controllable
- Other capabilities added

CTF operating parameters

Thermal input	1 MW_{th} (0.8 – 1.2MW_{th})
Furnace	Horizontally fired, refractory lined, water cooled, balanced draft
Dimensions	1m x 1m x 3m
Burner	Scaled MBEL Mk III Low-NO_X
Windbox temp.	300 to 330°C
Primary air temp.	80°C (70 to 90°C)
Tertiary : secondary	3.5:1 (1:1 to 7:1)
Overfire air	15% (0 to 25%)
Flue gas cleanup	High efficiency cyclone

RFCS Project RFS-PR-02003 : "ASSOCOGS"

"Assessment of Options for CO_2 Capture and Geological Sequestration"

• Start date (duration)	January 2004 (3 years)
• Project co-ordinator	E.ON UK
• Partners	Aristotle University of Thessaloniki Centre For Research and Technology Hellas CERECO IMCG International University of Nottingham IVD Stuttgart

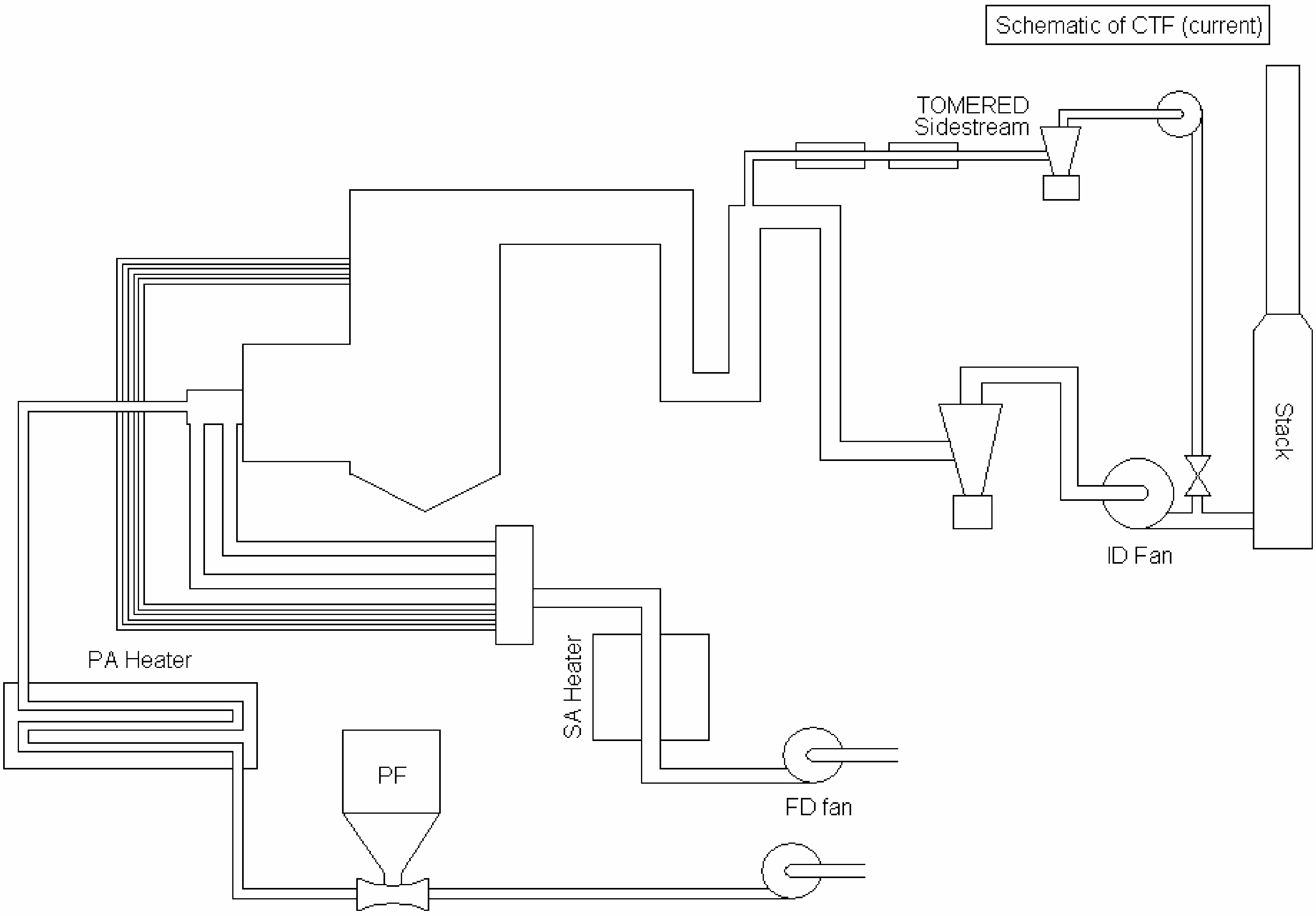
RFCS Project RFS-PR-02003 : "ASSOCOGS"

"Assessment of Options for CO_2 Capture and Geological Sequestration"

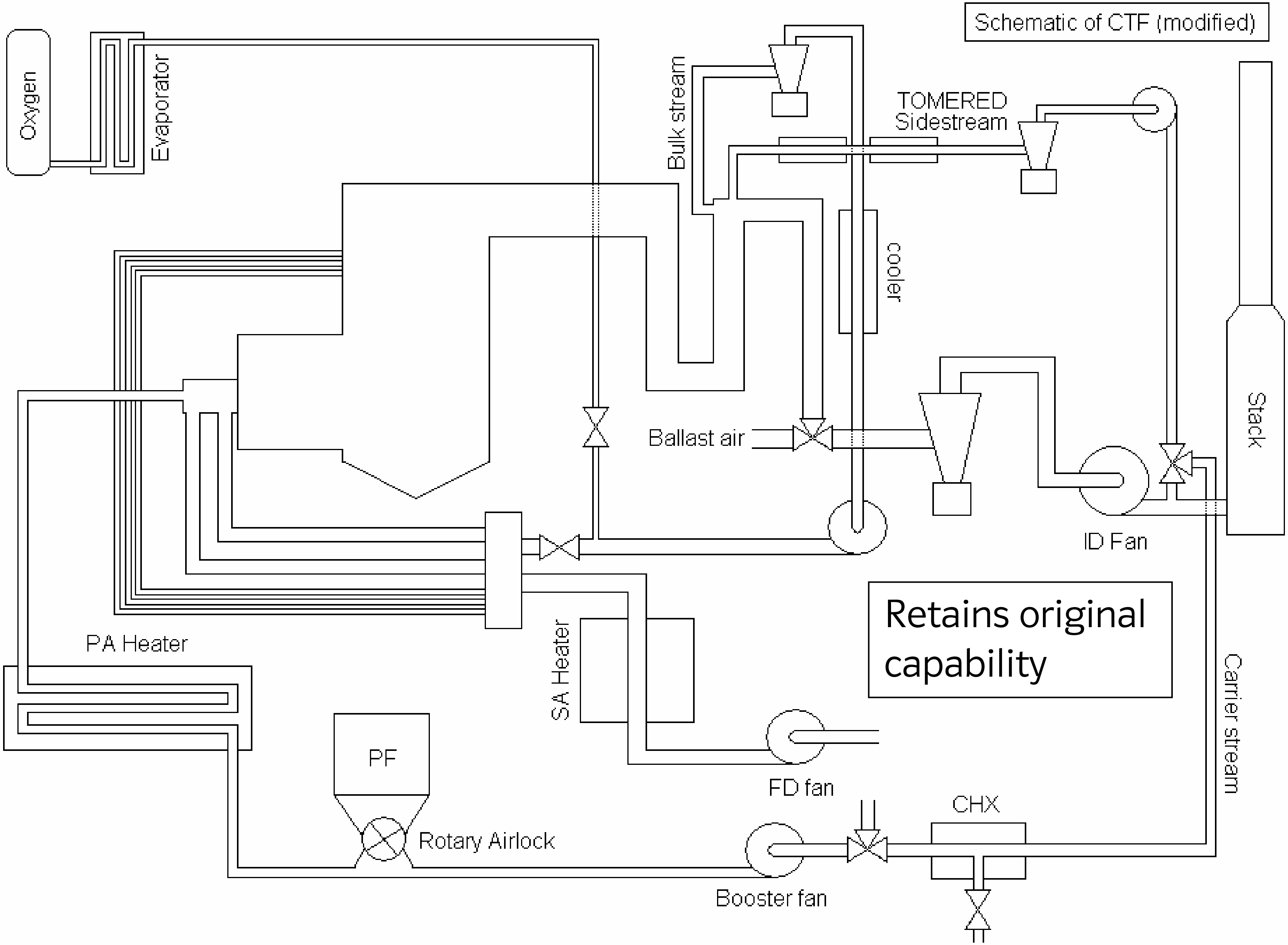
WP2 Oxyfuel combustion

- Review design of CTF for oxyfuel combustion
- Develop revised operational procedures
- Prepare detailed redesign
- Construct and commission CTF
- Refine operational procedures
- Perform parametric testing
- Review findings and implications

Original design



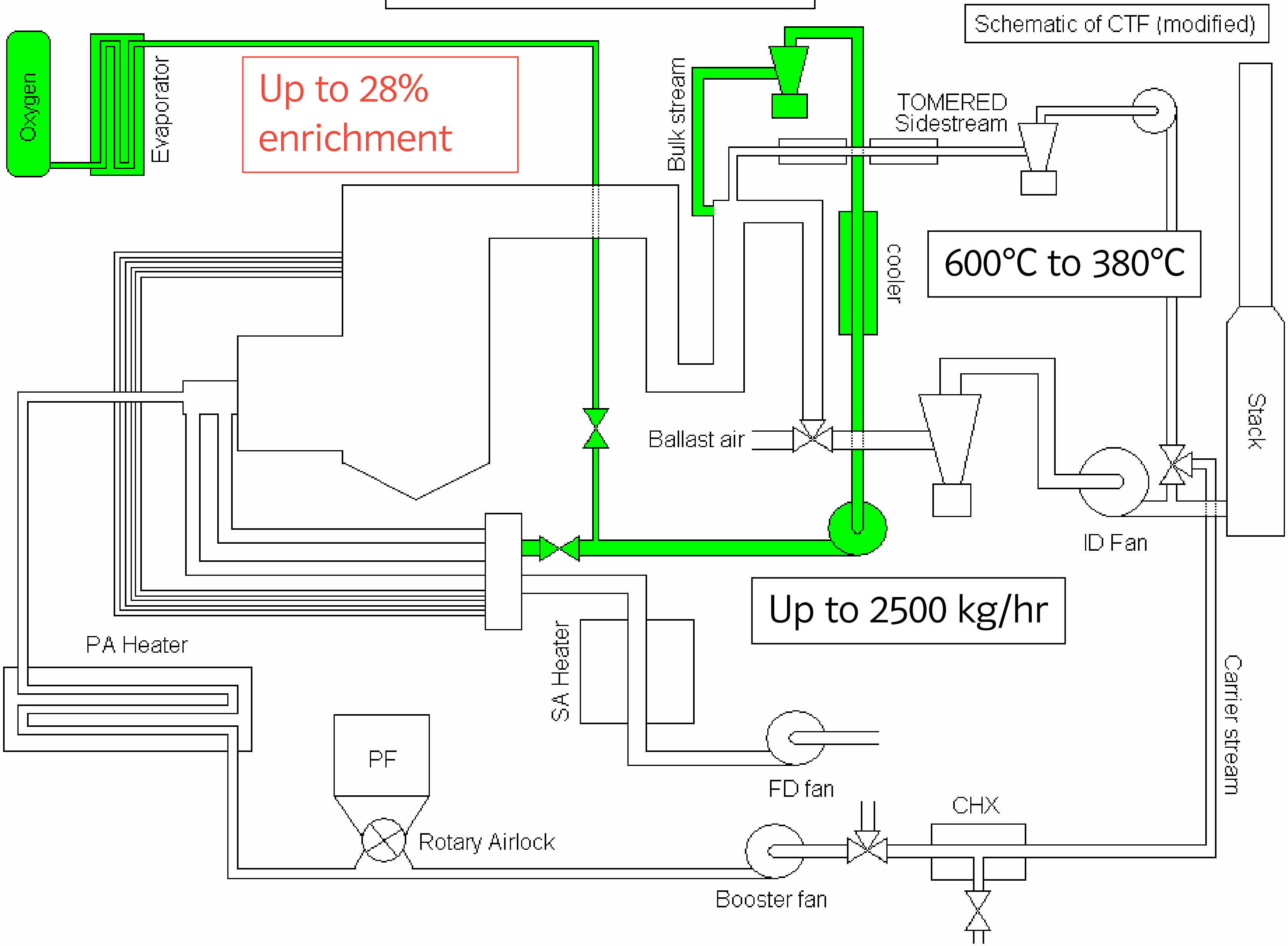
New design



Retains original capability

Secondary recycle

>90% capture efficiency
>600 °C



Primary recycle

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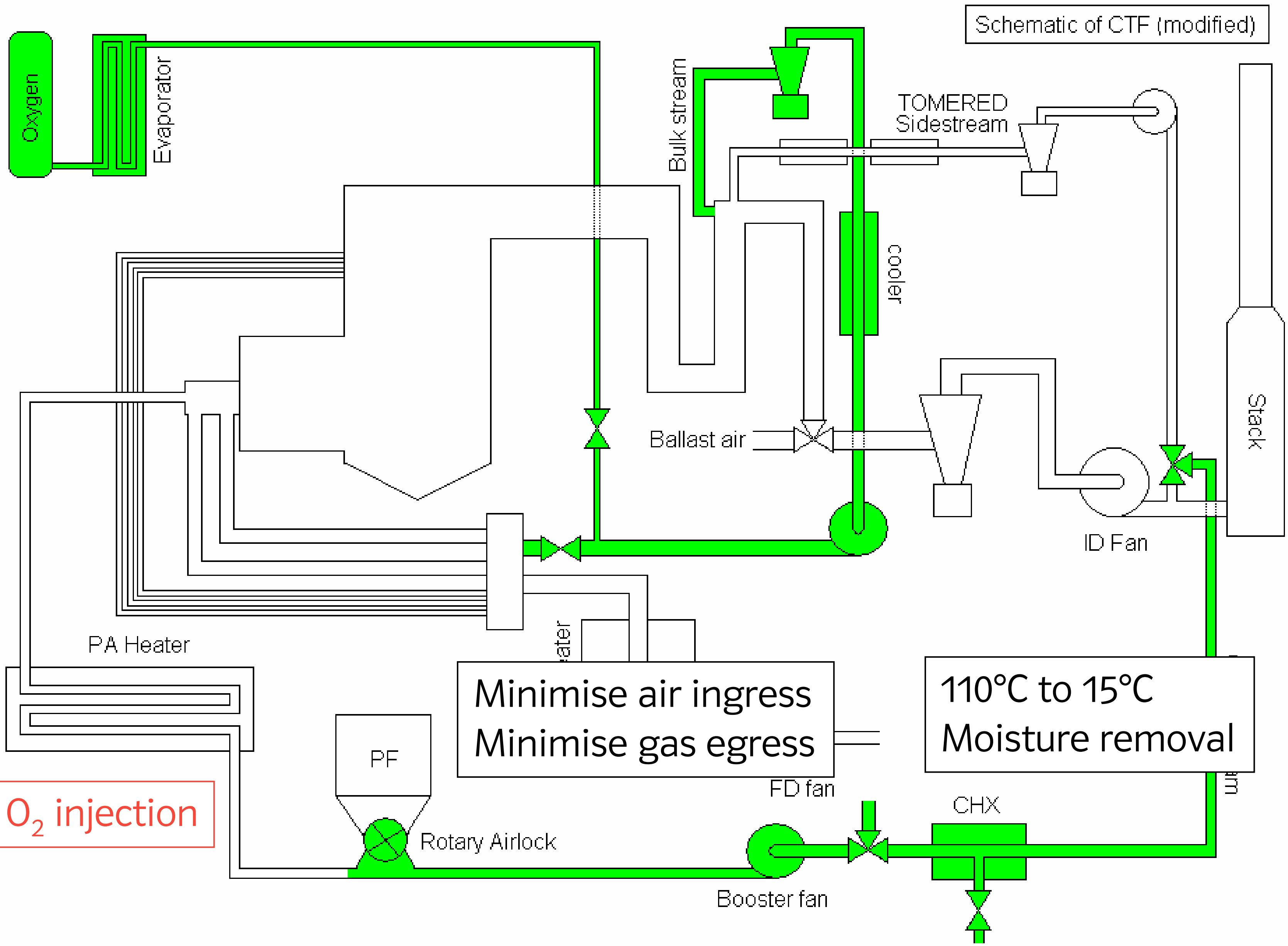

Minimise air ingress
Minimise gas egress

110°C to 15°C
Moisture removal

No O_2 injection

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Oxyfuel operating parameters

Secondary O_2 enrichment	21 to 28% (v/v, wet)
Primary O_2 enrichment	None (except O_2 in exhaust)
Overall enrichment	Up to 24% (v/v, wet)
Primary recycle rate	320 kg/hr (300 to 350 kg/hr)
Recycle ratio	75 to 85%
Burner stoichiometry	0.7 to 1.2

Limitations:

- No O_2 enrichment in primary recycle
- Relatively low enrichment limit in secondary recycle => overall
- No additional flue gas cleanup

Issues – design and operation

Safety

- Gas compositions
- Materials flammability, explosion risk
- CO_2/CO detection
- Flame detection
- Interlocks

Operation

- Switchover
- Feedback
- Burner trips and blackouts

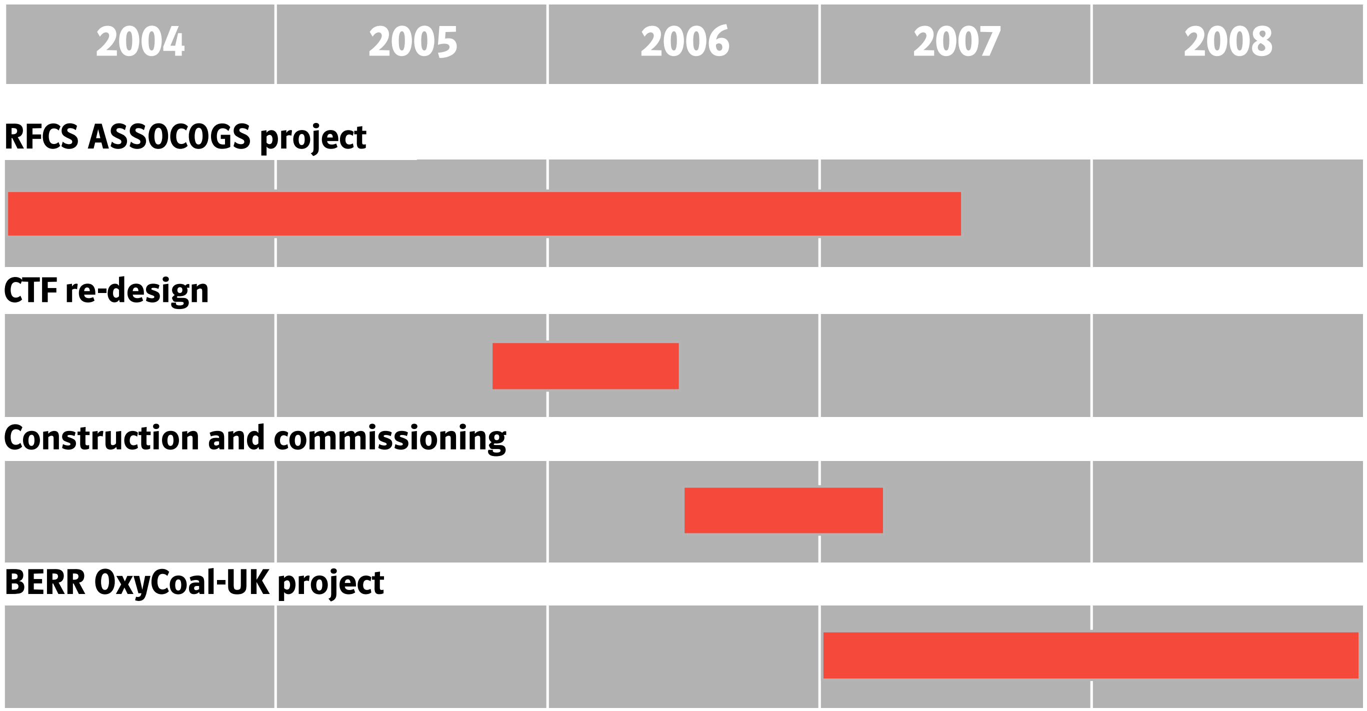
Process

- Coal feeding
- Heat extraction
- Particulate removal
- Materials – high temperature, O_2 purity
- Air ingress
- Moisture removal

Control and Instrumentation

- Mass flow – via density
- O_2 concentration

Development timetable



BERR Technology Programme Project 404 : OxyCoal-UK (Phase I)

• Start date (duration)	January 2007 (2 yrs)
• Project co-ordinator	Doosan Babcock Energy
• Partners	E.ON UK, RWE npower, Air Products, Imperial College London, University of Nottingham, BP
• Sponsors	Scottish and Southern Energy, Scottish Power, Drax Power, EDF Energy, DONG Energy

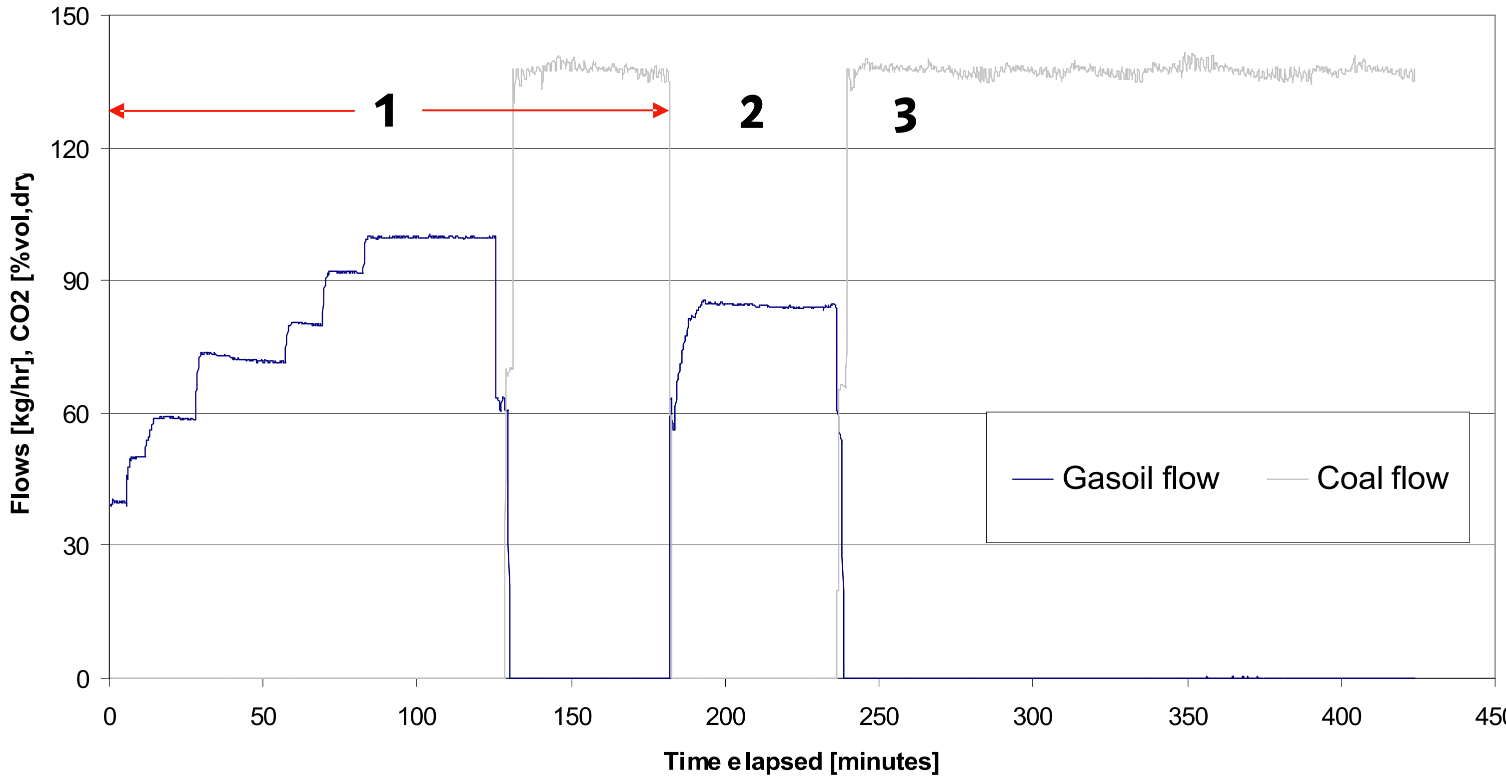
BERR Technology Programme Project 404 : OxyCoal-UK (Phase I)

WP2 Furnace Design and Operation

- Objective: To determine the impact of oxyfuel firing on combustion, slagging, fouling and high temperature corrosion
  - WP 2.1: 1 MW_{th} Pilot-Scale Tests
  - WP 2.2: Ash Characterisation
  - WP 2.3: Corrosion Tests

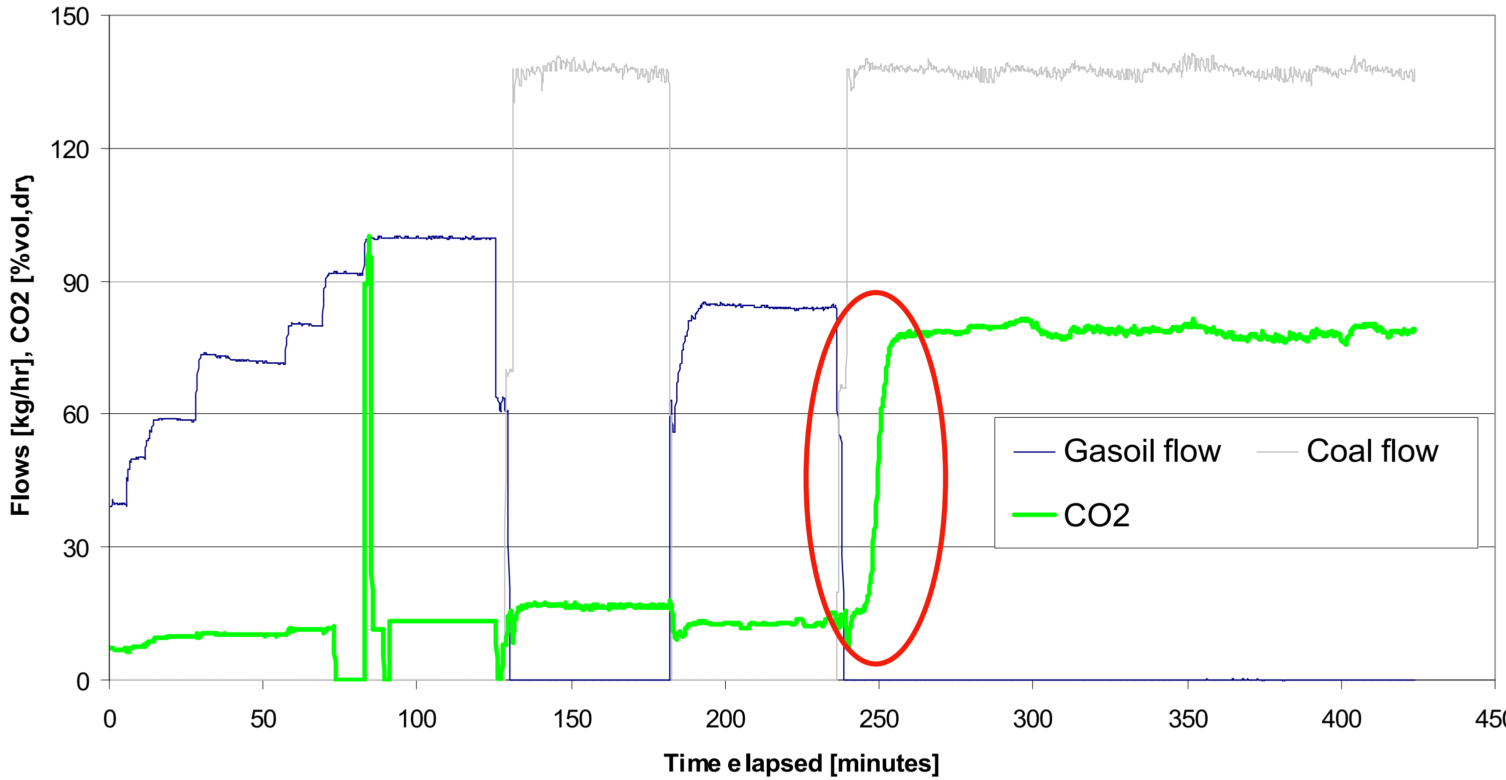
Results

Startup and changeover (1)



1. Warm up on gasoil, then switchover to coal for air baseline test
2. Revert to gasoil during switchover of carrier stream
3. Revert to coal for full switchover (bulk)

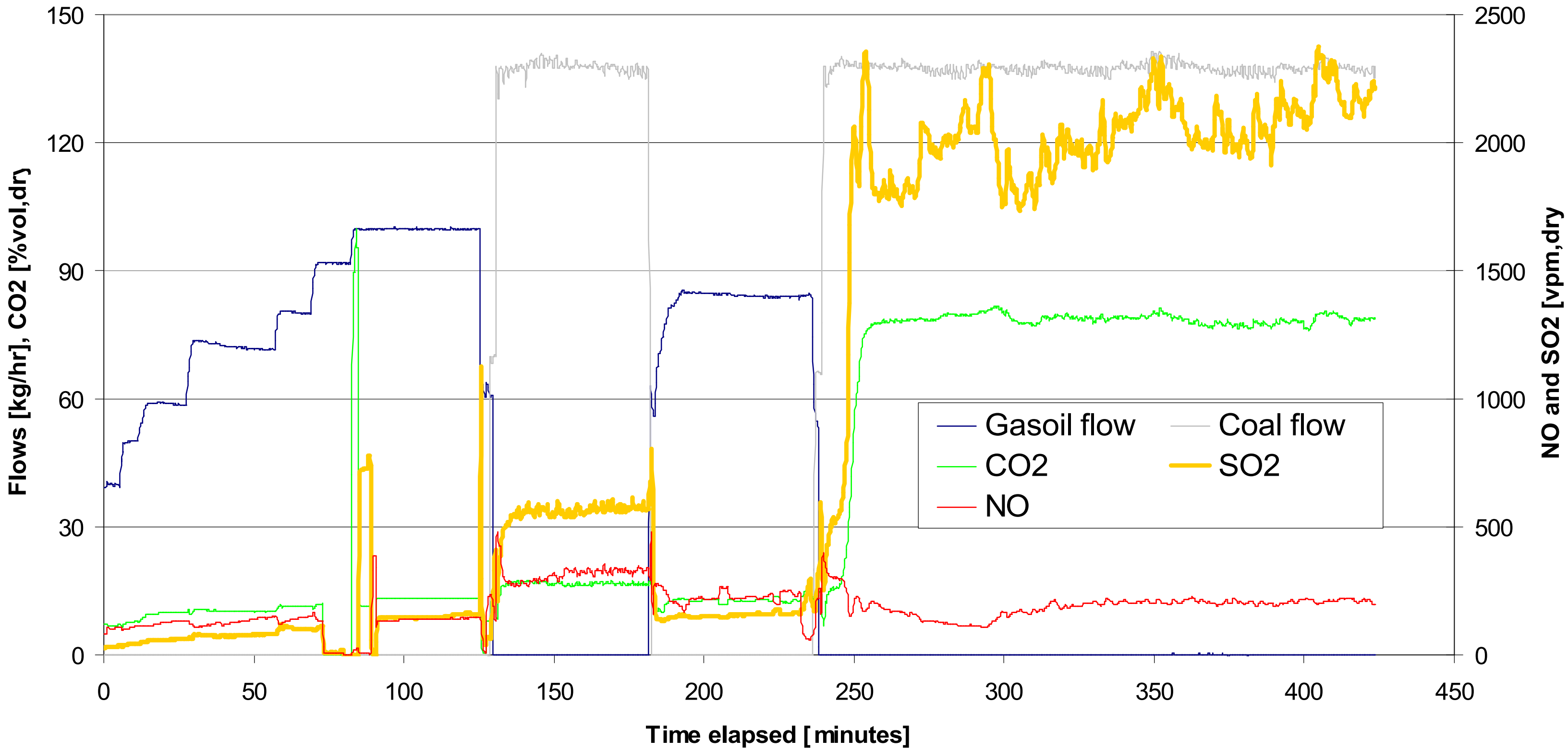
Startup and changeover (2)



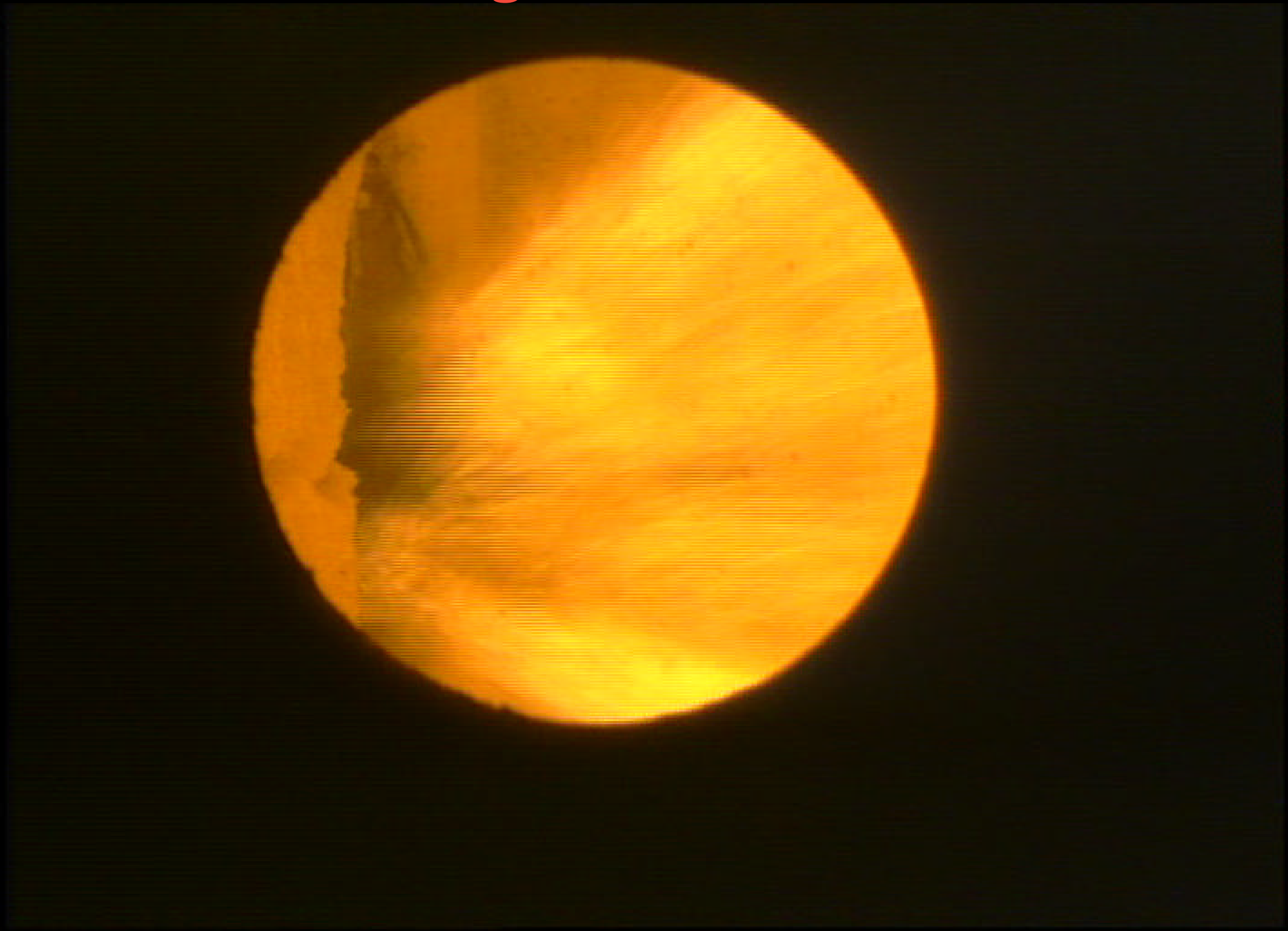
CO_2 [%vol,dry]	Gasoil, air = 14	Coal, air = 17	Coal, oxyfuel = 80

Changeover and CO_2 concentration response time <10 minutes

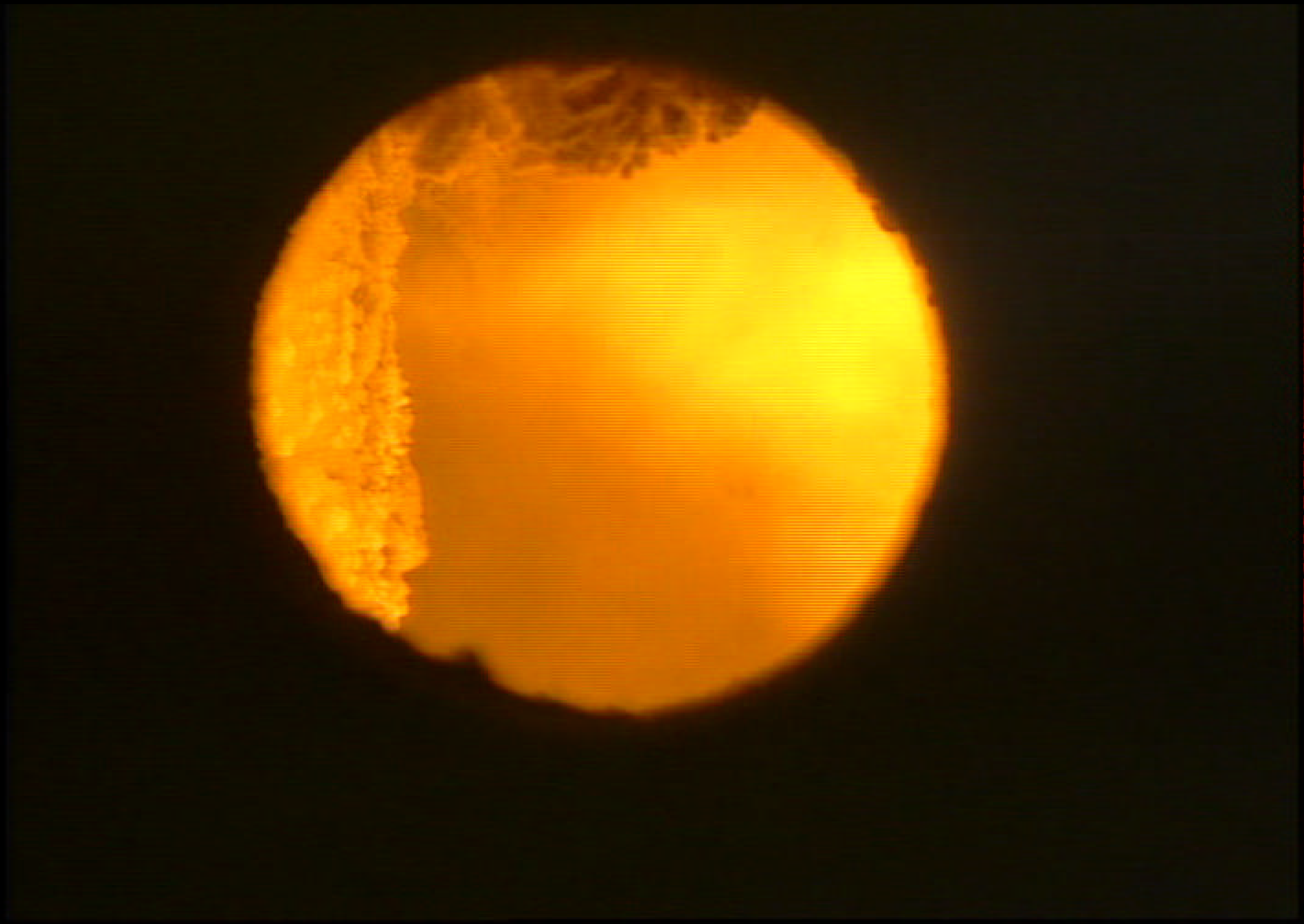
Startup and changeover (3)



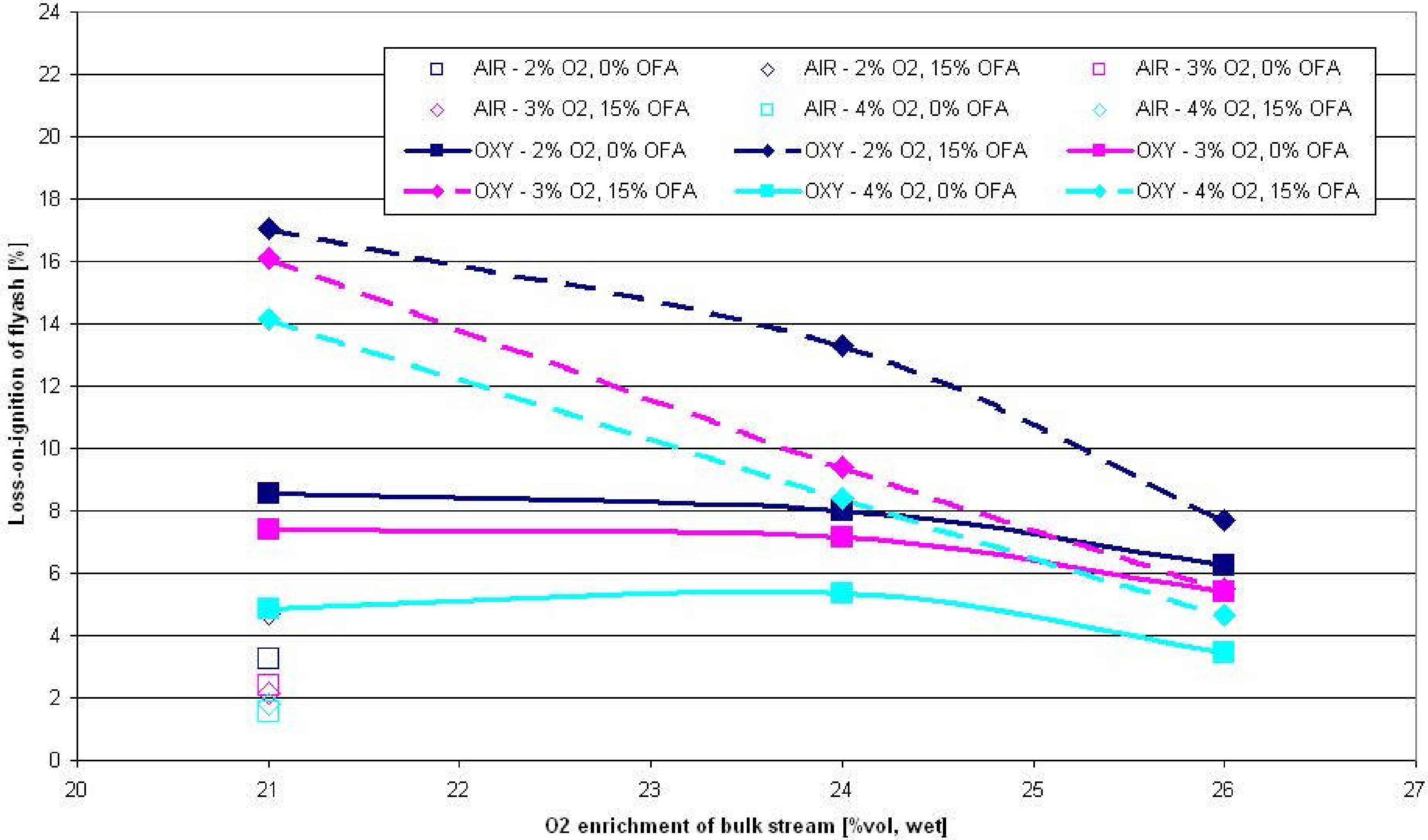
Still image of flame (air)



Still image of flame (oxyfuel)



Burnout



AIR - 2% O2, 0% OFA
AIR - 2% O2, 15% OFA
AIR - 3% O2, 0% OFA
AIR - 3% O2, 15% OFA
AIR - 4% O2, 0% OFA
AIR - 4% O2, 15% OFA
OXY - 2% O2, 0% OFA
OXY - 2% O2, 15% OFA
OXY - 3% O2, 0% OFA
OXY - 3% O2, 15% OFA
OXY - 4% O2, 0% OFA
OXY - 4% O2, 15% OFA
Loss-on-ignition of flyash [%]
O2 enrichment of bulk stream [%vol, wet]
0
2
4
6
8
10
12
14
16
18
20
22
24
20
21
22
23
24
25
26
27

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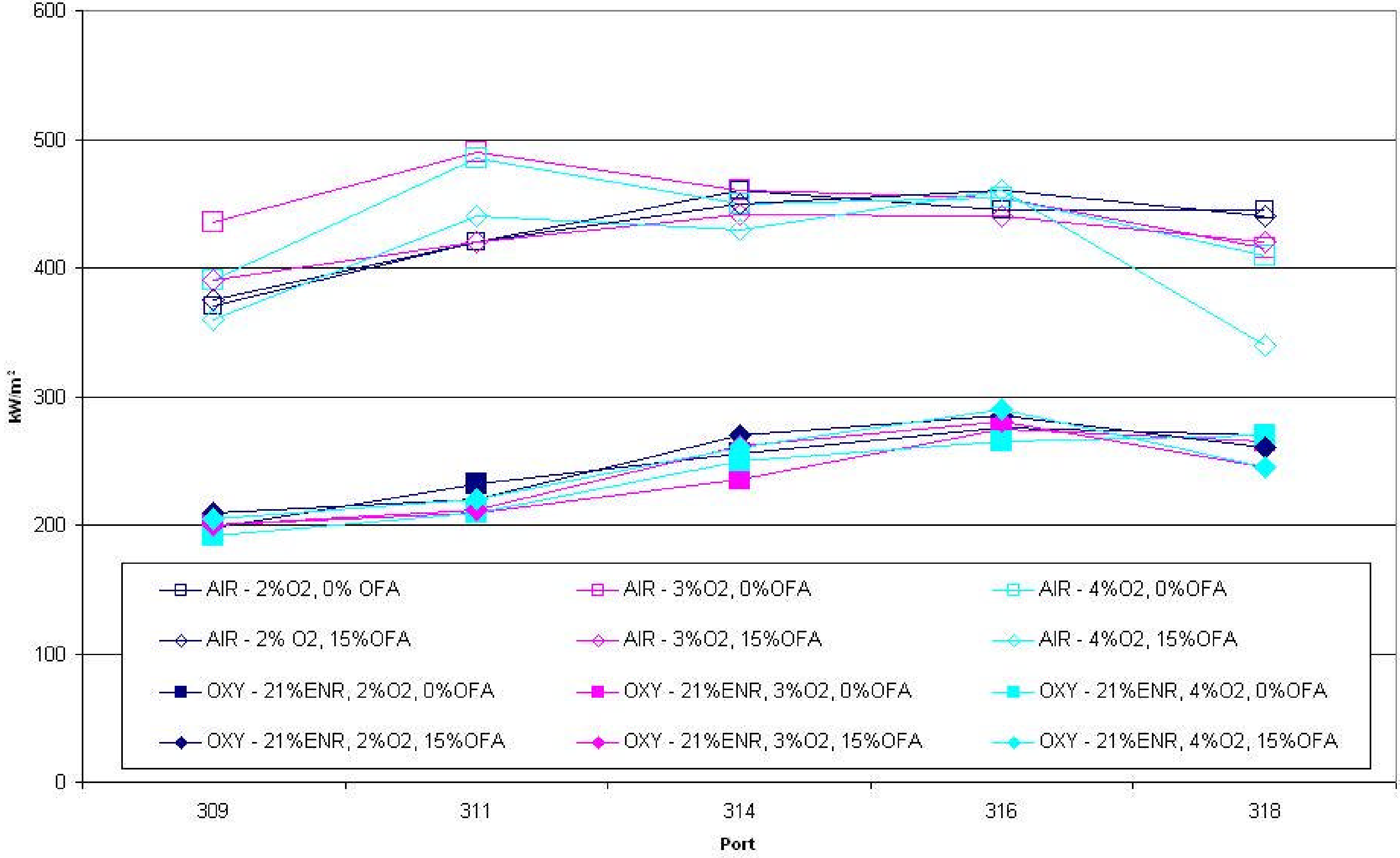
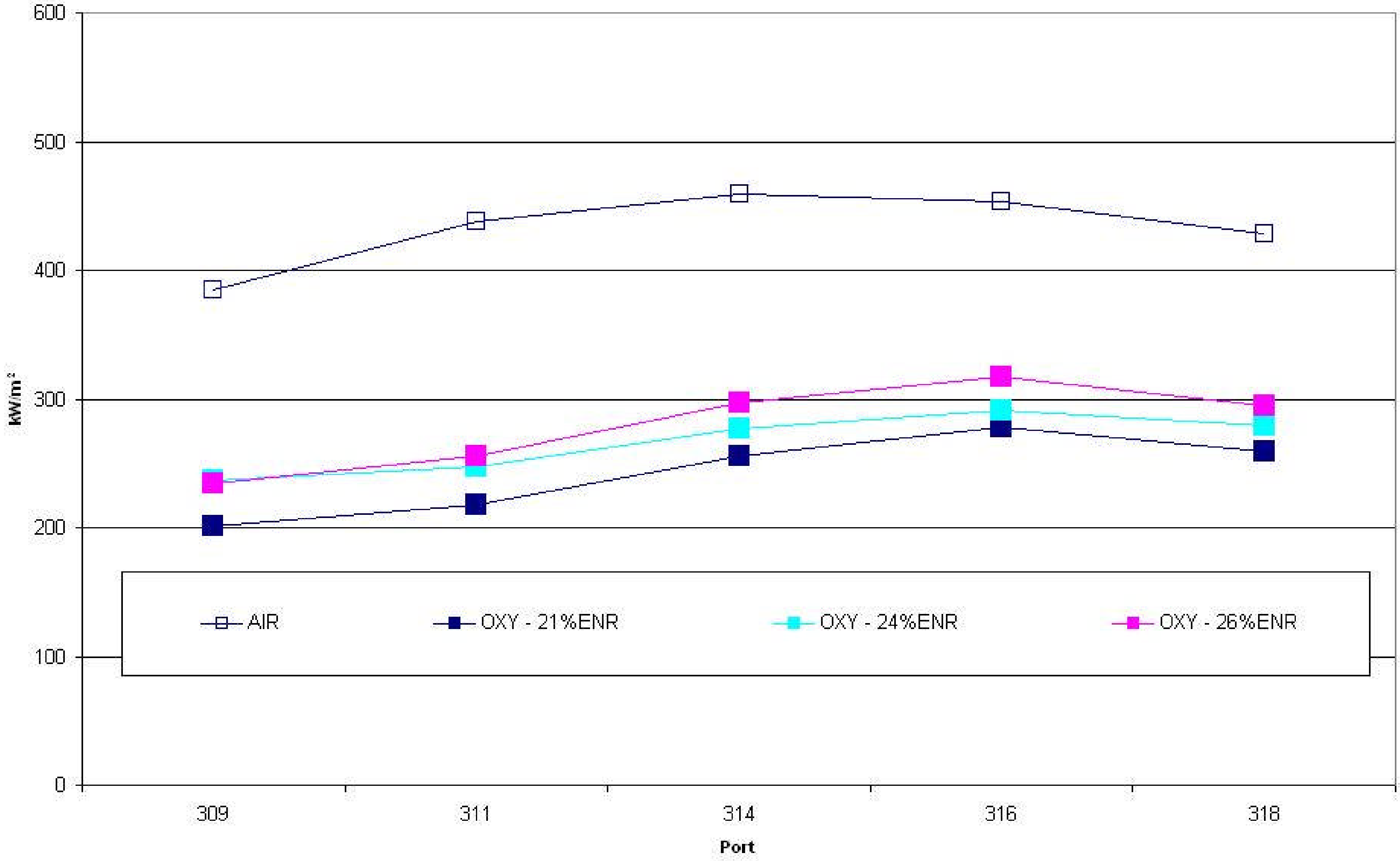
Furnace wall heat flux (1)

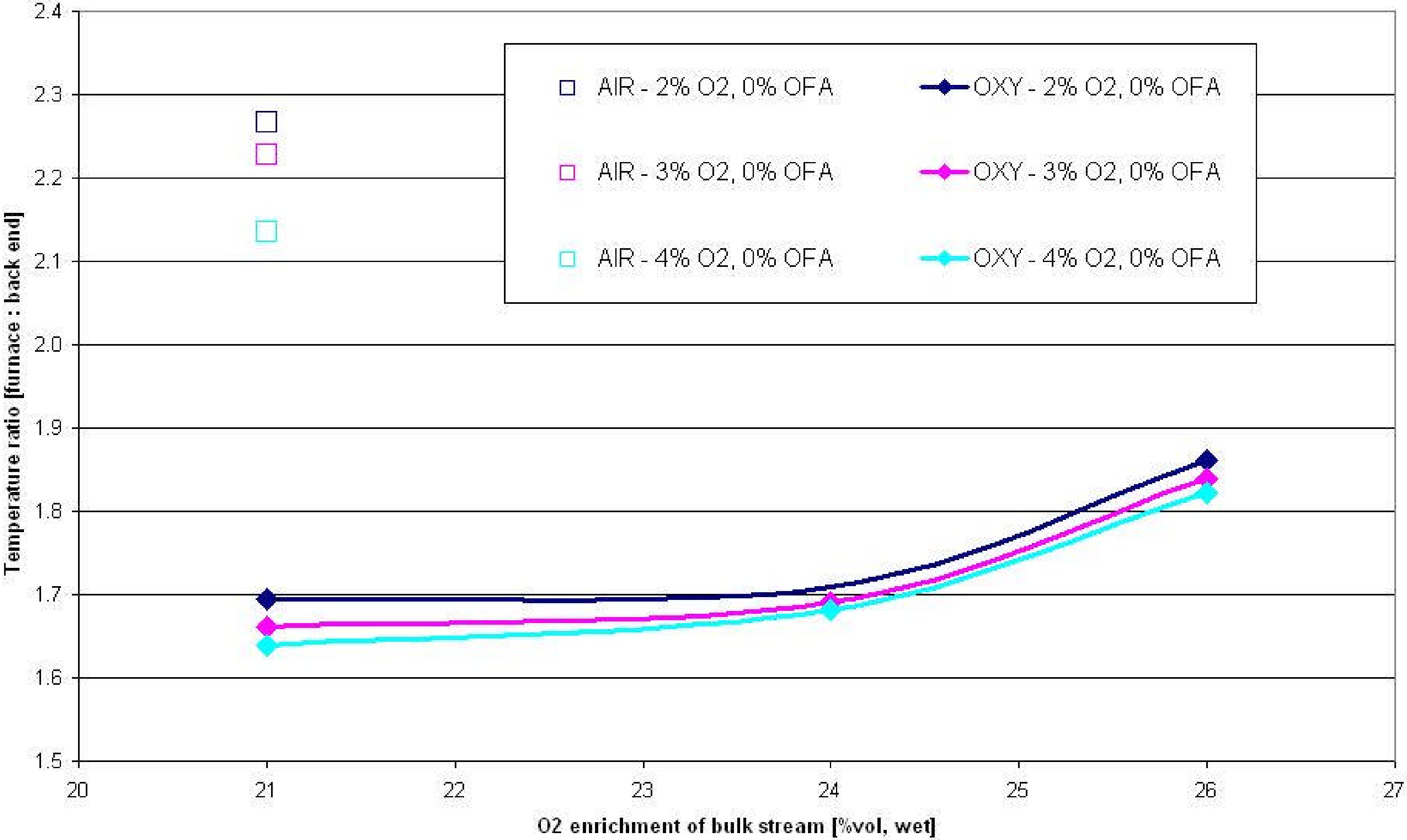


Furnace wall heat flux (2)

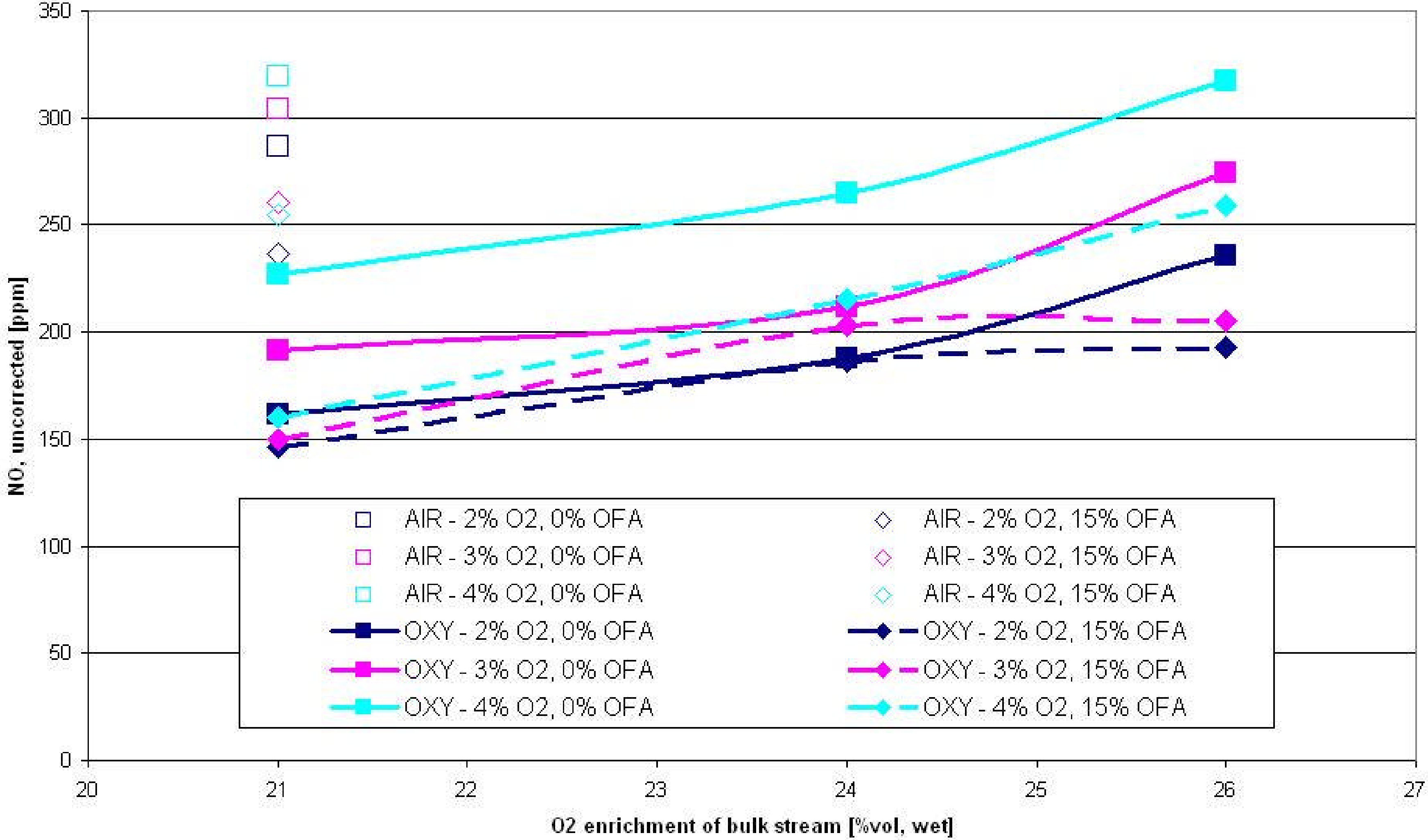


UK

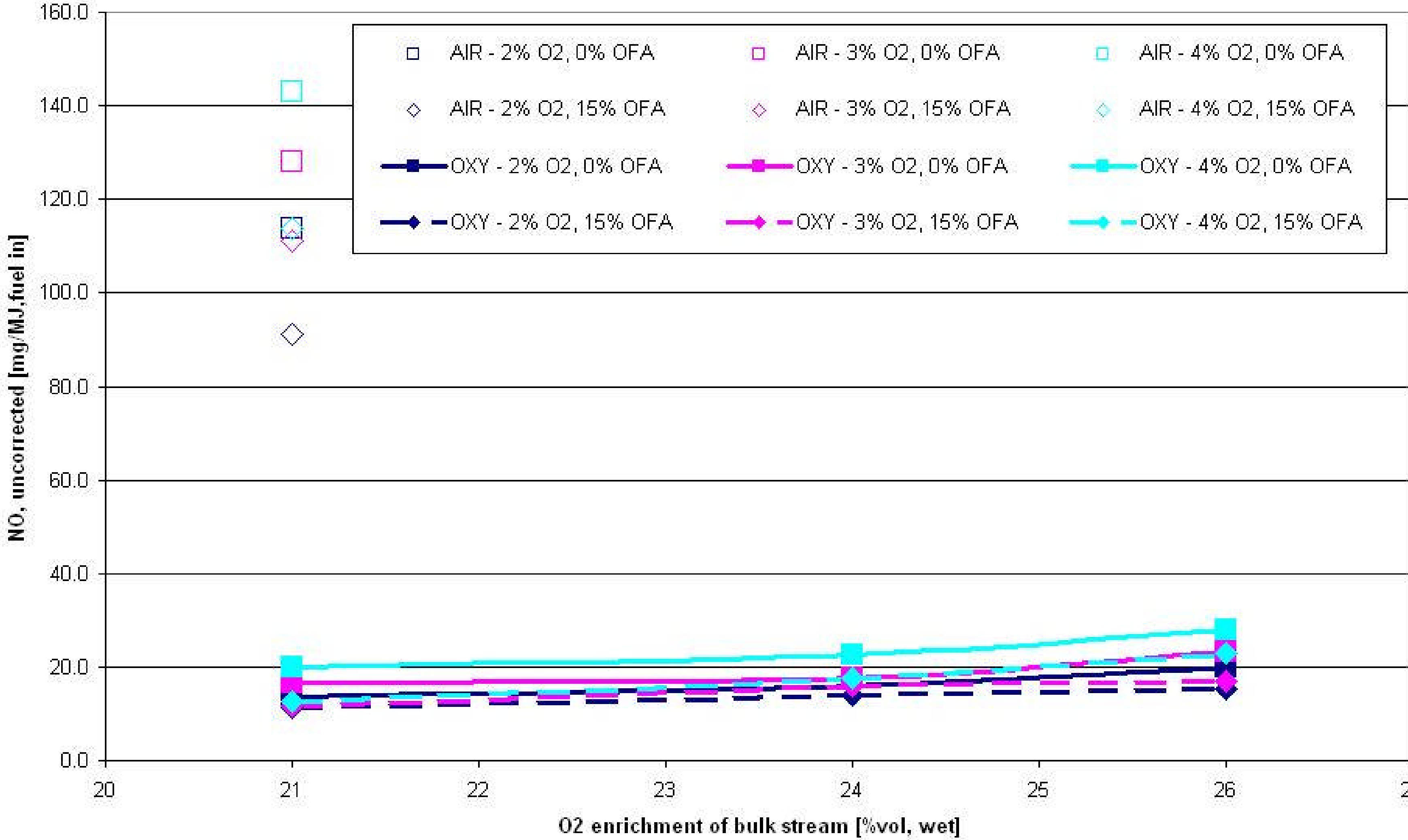
Heat distribution



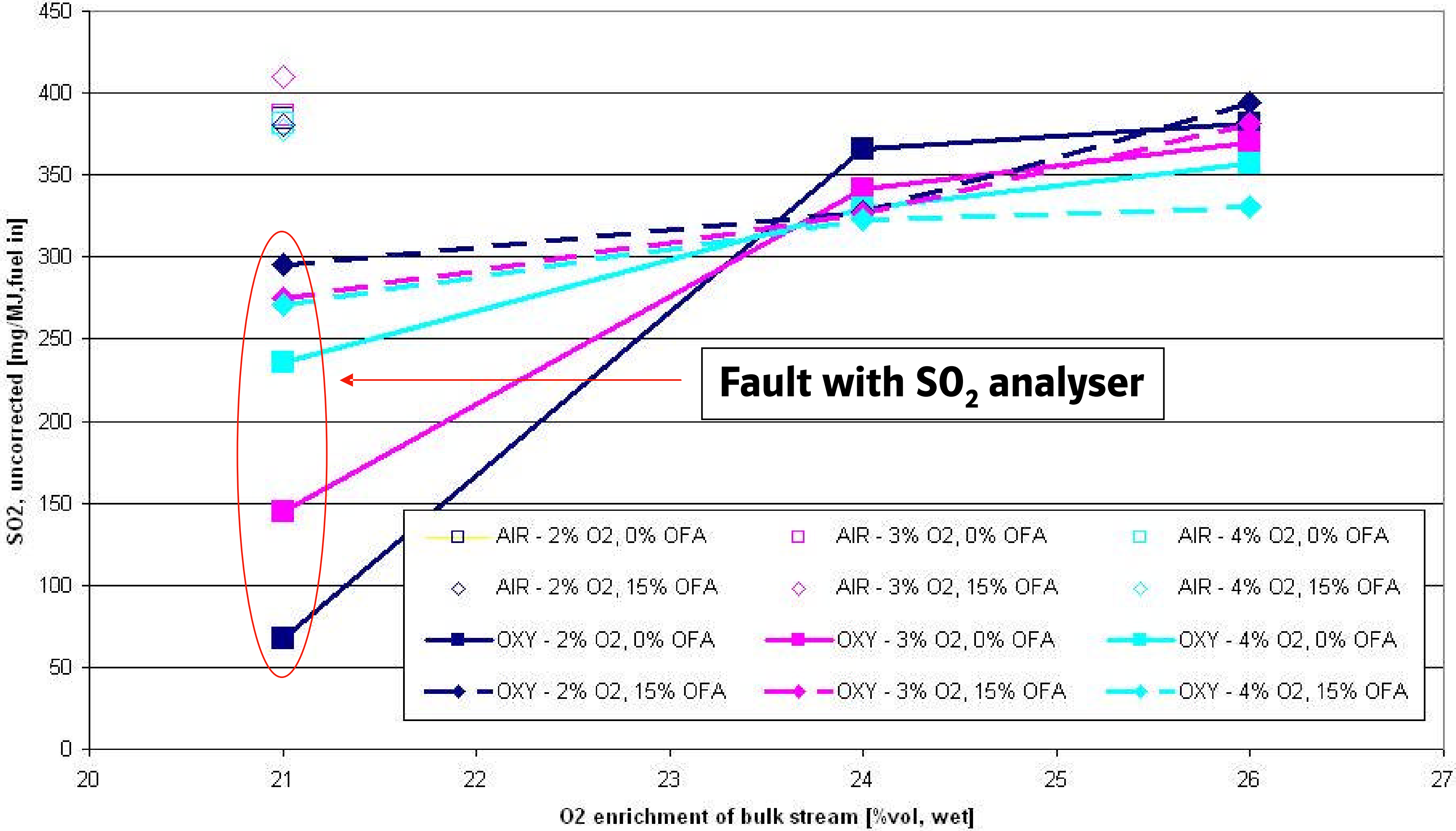
Emissions – NO (1)



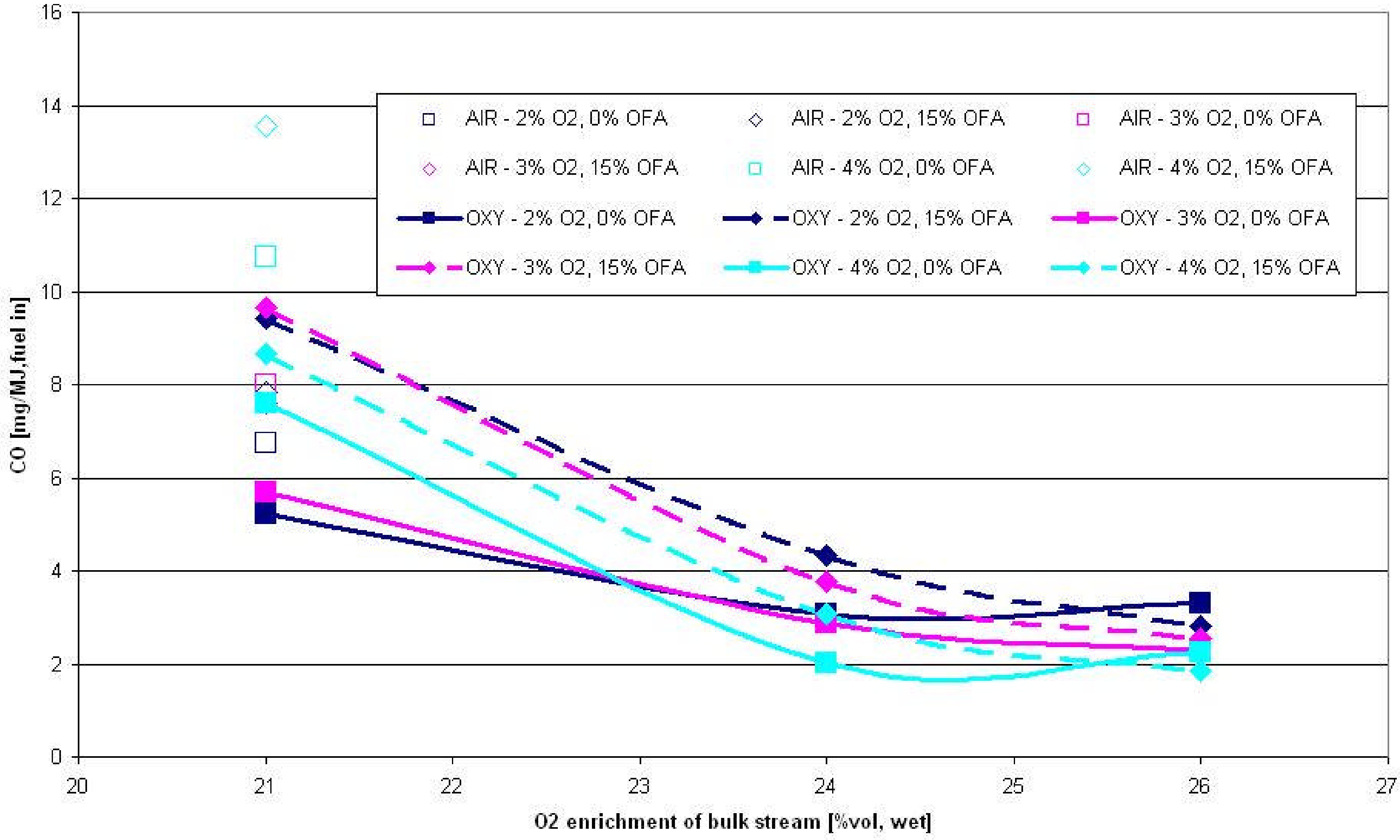
Emissions – NO (2)



Emissions – SO_2

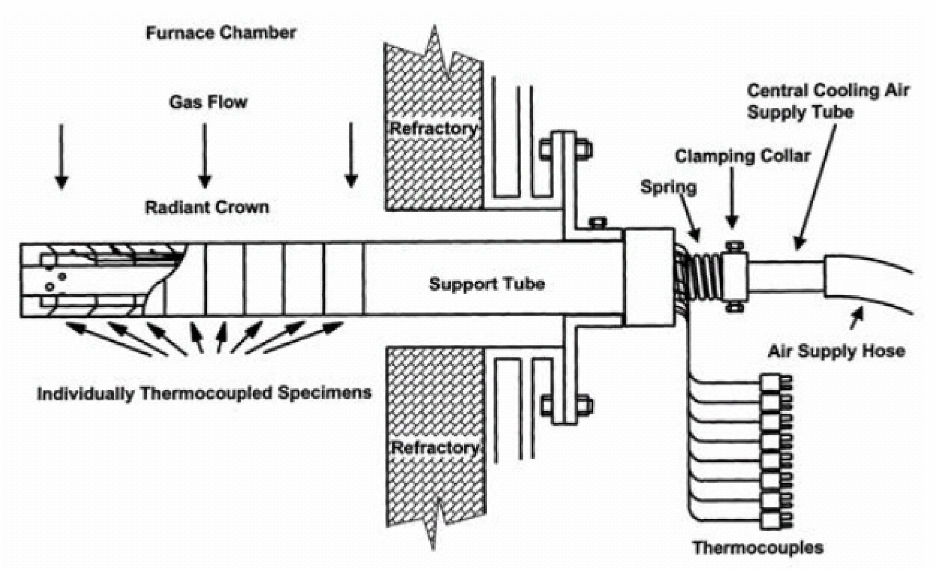


Emissions - CO



Corrosion

- 50 hour test – method developed in collaboration with EPRI in 1990's
- Can be reliably extrapolated to predict full scale impacts
- Samples currently being analysed



- Test materials
  - Furnace wall samples - HR3C, T91, IN671, 15Mo3, T23 (400 to 525°C)
  - Superheater/reheater samples - T22, TP347HFG, HR3C, T91, E1250, (San25), (IN740) (450 to 650°C)

Ash behaviour

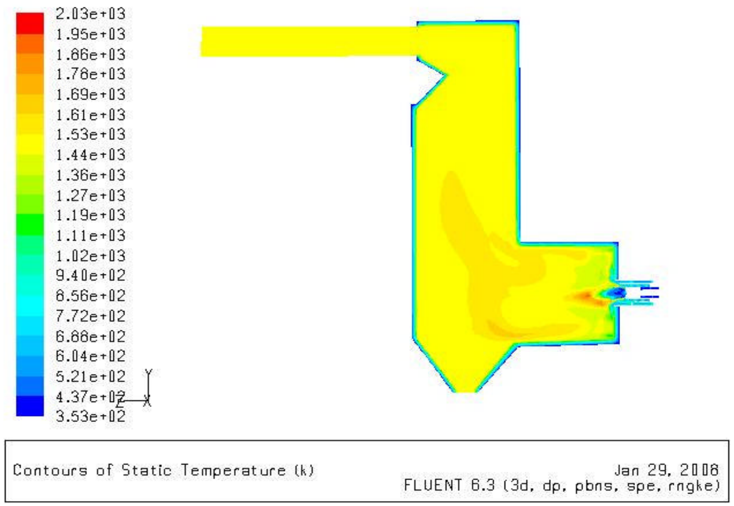
- Deposition samples collected and analysed by ICL, principally by CCSEM and XRD, to determine chemical composition and degree of sintering to investigate the impact of oxyfuel combustion on coal ash transformation and deposition

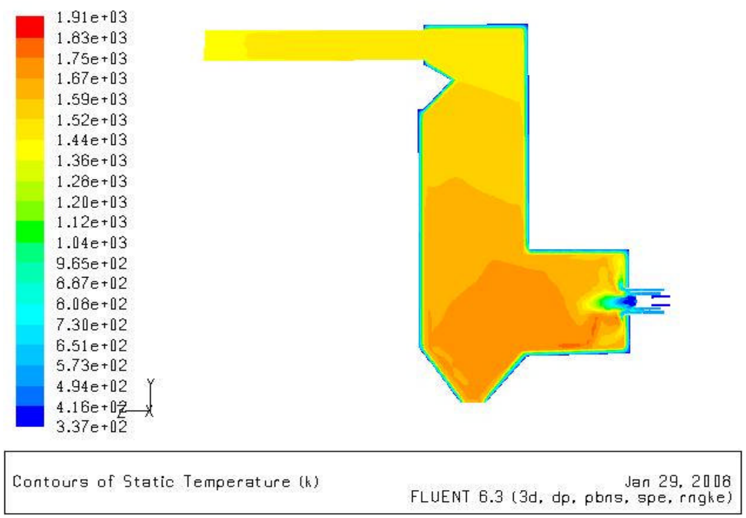
- Flyash samples also sent to NETL for analysis

- Results:
  - Early indications (lower levels of mineral transformation) are that temperature effects dominate

Modelling

- Burner and furnace being modelled by University of Leeds
- Work in early stages – incorporating ongoing research in combustion fundamentals
- Validation during next test period





Conclusions and plans for the future

- 1 MW_{th} facility fully commissioned and capable of testing emissions, thermal environment, burnout, deposition and corrosion.
- Stable flame established without burner O_2 addition - but poorly attached - will further examine performance with O_2 enrichment to establish overall optimum.
- Some reduction in NO_X concentrations - dramatic reduction in NO_X flux.
- Deposit significantly more ’sticky’, but no apparent change to bulk chemistry - impact of fouling propensity or changed T profile?
- Further work planned on impacts of fuel quality, enrichment, and combustion staging on deposition, corrosion and emissions.

- Based on experience gained so far, planning to increase enrichment capability.

Acknowledgements

- European Commission (Research Fund for Coal and Steel)
- UK Department for Business, Enterprise and Regulatory Reform
- Colleagues within E.ON
- Partners within ASSOCOGS and OxyCoal-UK projects
- NETL
- University of Leeds

Thank you for your attention!
Any questions?

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Fundamental Studies and Pilot-Scale Evaluation of Oxycoal Firing in Circulating Fluidized Bed Boilers

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Institute for Clean & Secure Energy

The University of Utah

Oxy-Coal Combustion at the University of Utah

- **University of Utah has several key programs in this area**
  - **UofU Faculty involved: Eddings, Eyring, Sarofim, Smith, Wendt, Whitty**
  - **Utah Clean Coal Progam (U.S. DOE)**
    - Oxy-Coal Firing of Pulverized Coal *(Wendt/Eddings)*
      - *Presentation in parallel session this morning*
    - Oxy-Coal Firing in Circulating Fluidized Beds *(Eddings/Sarofim)*
    - Chemical Looping Combustion of Coal *(Eyring/Whitty/Sarofim)*
    - Simulations of Oxy-Firing of Pulverized Coal *(Smith)*
  - **Praxair, Inc.**
    - Development of Coal Combustor for Oxygen Transport Membrane (OTM) Technology - w/DOE *(Eddings/Sarofim)*
    - Pilot-Scale Oxy-Coal Combustion Studies *(Eddings/Wendt)*
  - **DOE/ASC**
    - Simulations of Oxy-Coal Fired Boilers *(Smith)*
  - **Additional new programs pending**

Oxy-coal Test Facilities

300 kW Circulating Fluid Bed

75 kW PC-Fired

1.5 MW PC-Fired

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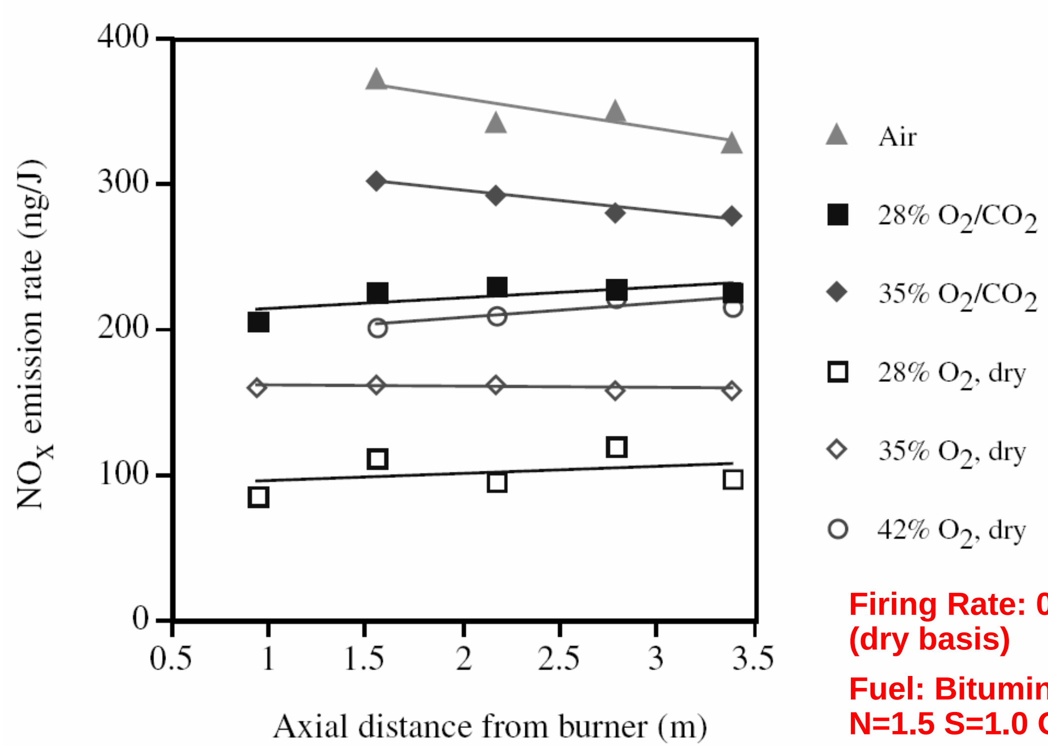
Motivation for Fundamental Studies



Firing Rate: 0.21 MW with 5% excess O2 (dry basis)

Fuel: Bituminous coal C=77.7% H=5.0 N=1.5 S=1.0 O=6.9 Ash=7.9

- Reduced NOx emission rates under oxyfiring conditions
- Differences in NOx emission rate at same O_2 level but different diluent source
- Previous UofU studies on effects of NO, O_2 concentration on Char N conversion

Croiset & Thambimuthu, Fuel 80 (2001) 2117-2121

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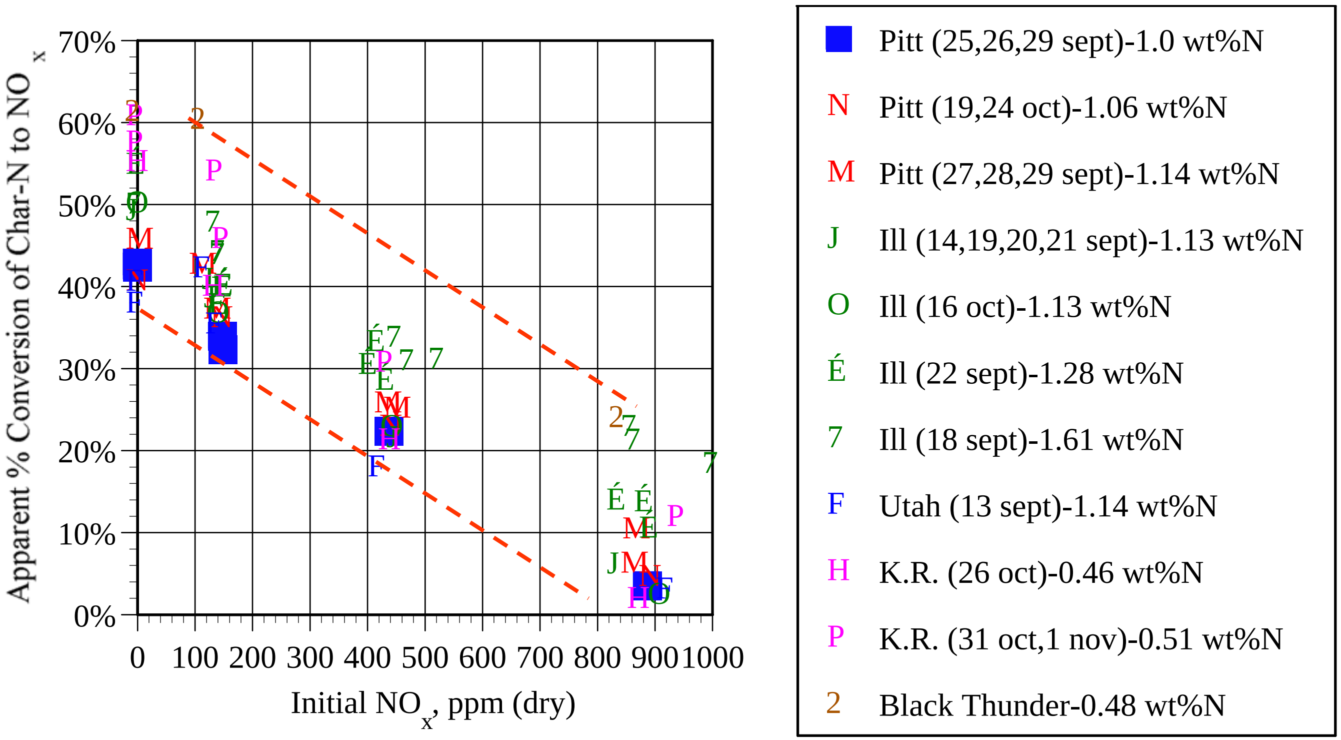
Influence of Initial NO on Char N Conversion



Data of Spinti (1997) taken in 25 kW down-fired combustor at University of Utah indicates strong effect of local NO on char N conversion.

Background

- Research Program has two primary objectives:
  - obtain fundamental rate and fuel nitrogen conversion information for oxycoal-fired circulating fluidized bed (CFB) boilers
    - Need for understanding of effect of gas phase composition on fuel NOx formation under oxycoal firing conditions
  - obtain model validation and process characterization data from pilot-scale operation of an oxycoal-fired CFB
- Funding provided by
  - U.S. DOE – Utah Clean Coal Program
  - Praxair, Inc.

Fundamental CFB Efforts

- Goal:
  - to identify key mechanisms for NOx formation in oxy-coal combustion systems, and evaluate the interaction between surface N complexes and CO_2 and O_2
- Tasks
  - Design/construct single-particle fluid-bed reactor
  - Perform experiments with coal, coal chars and model chars
    - Gas analysis using FTIR
    - Solids analysis using FTIR, XPS
  - Model char preparation
    - Pure nitrogen-bearing organic compound (polyacrylonitrile)
    - Create chars under different conditions
    - Characterize initial form of N in char via FTIR, XPS
  - *Ab initio* calculations
    - Investigate surface N behavior under oxy-firing conditions

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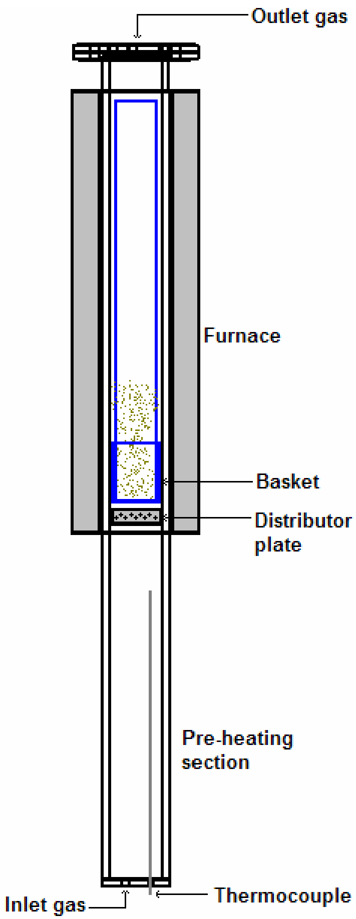
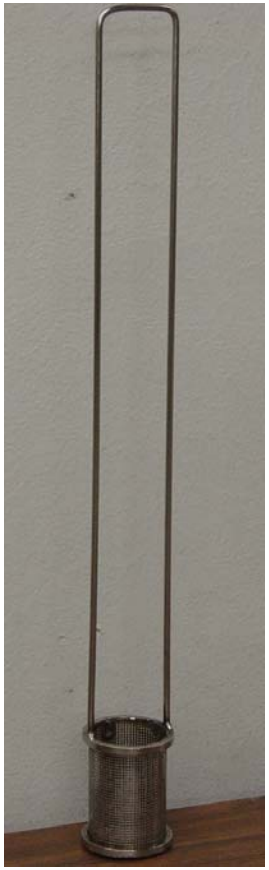
Single Particle Reactor





- Fuel particle larger than bed material; bed material moves freely through basket
- Basket used to remove fuel particle at different times during transient experiment for subsequent characterization (FTIR, XPS)
- Gas composition analyzed on-line by FTIR

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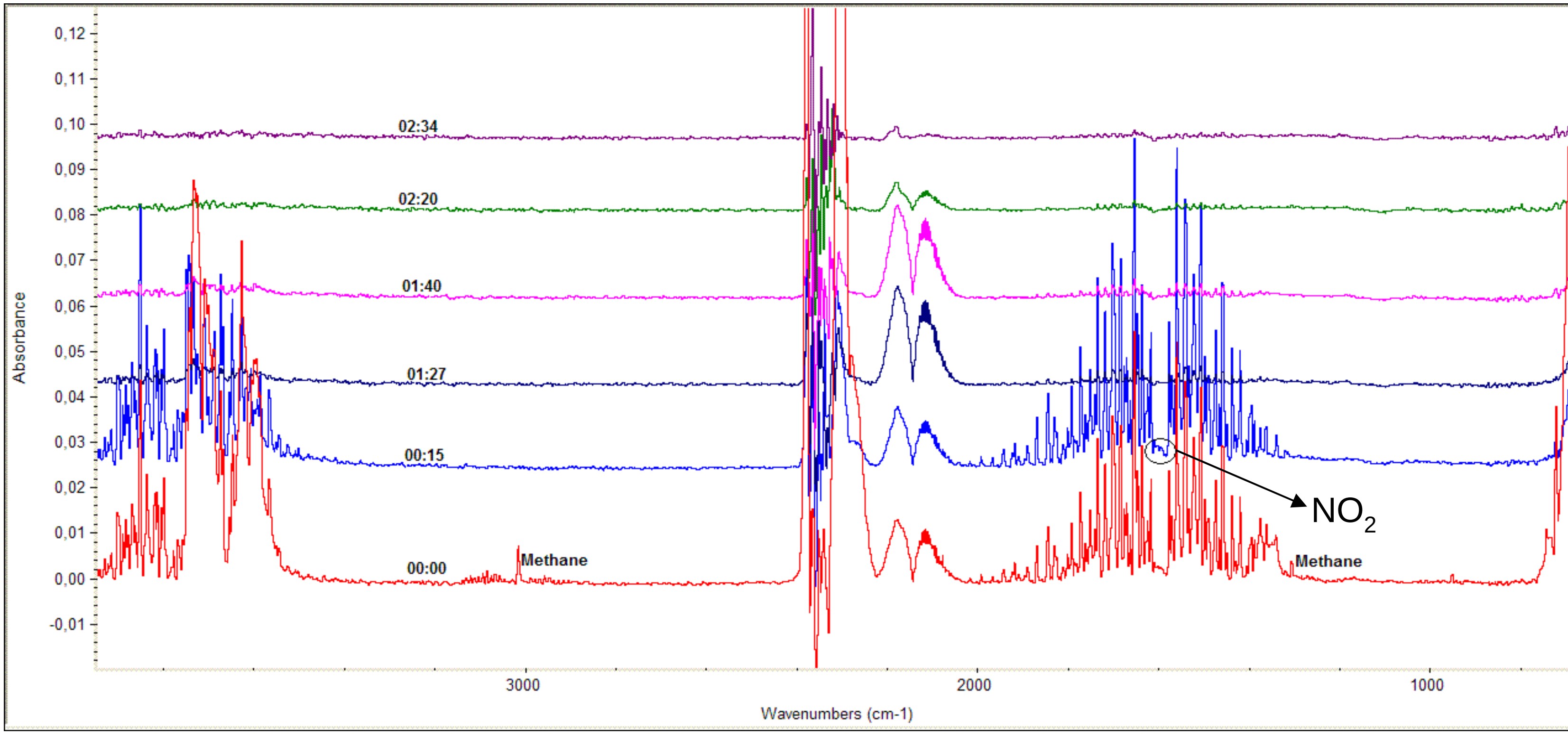
Preliminary Results

Single Particle – Louisiana Lignite

FTIR Spectra at Various Reaction Times

Oxidizer Composition: 50% O_2 - 50% CO_2



Very small amount of NO_2

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Single Particle – Louisiana Lignite

FTIR Spectra at Various Reaction Times

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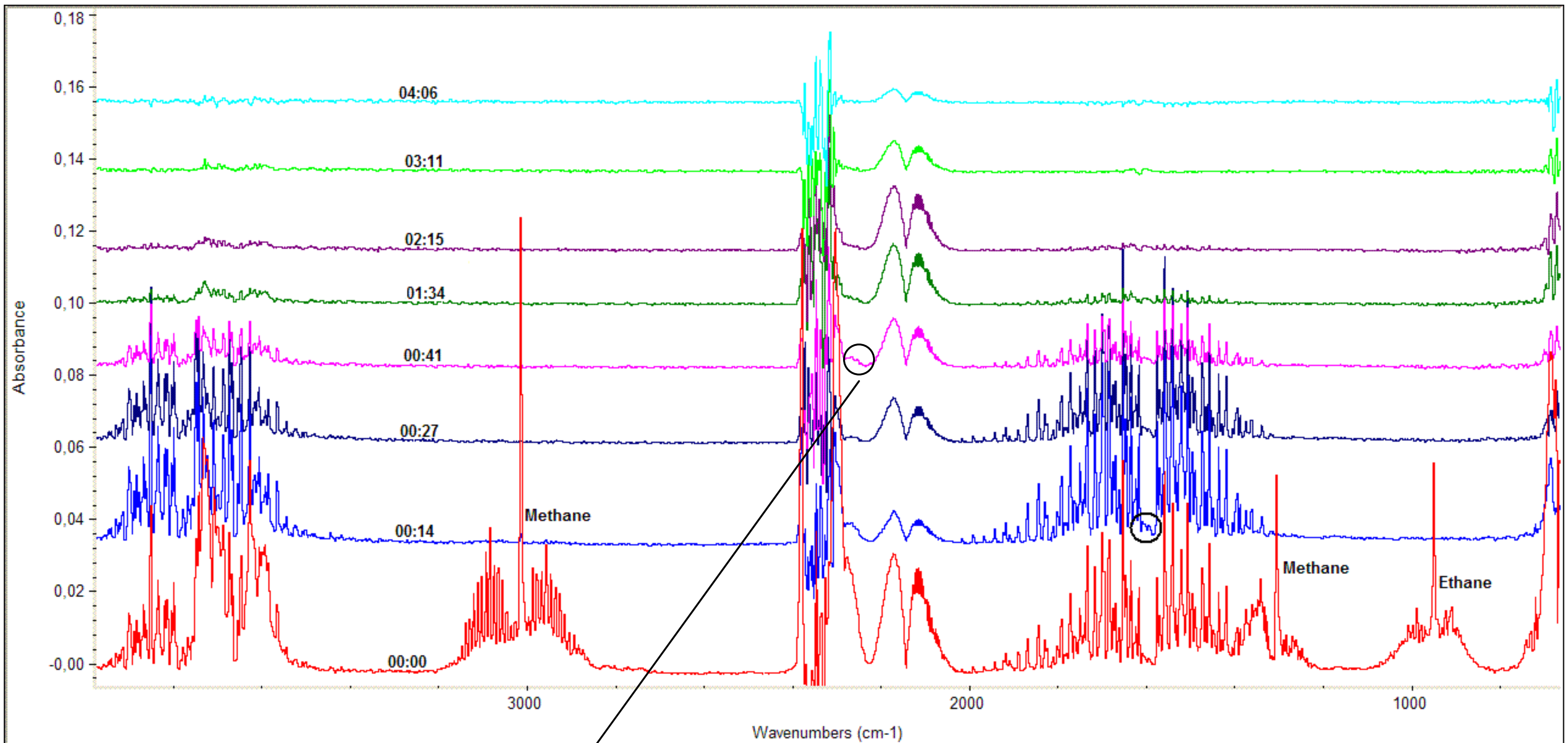
Oxidizer Composition: 25% O_2 - 75% CO_2



N_2O formation

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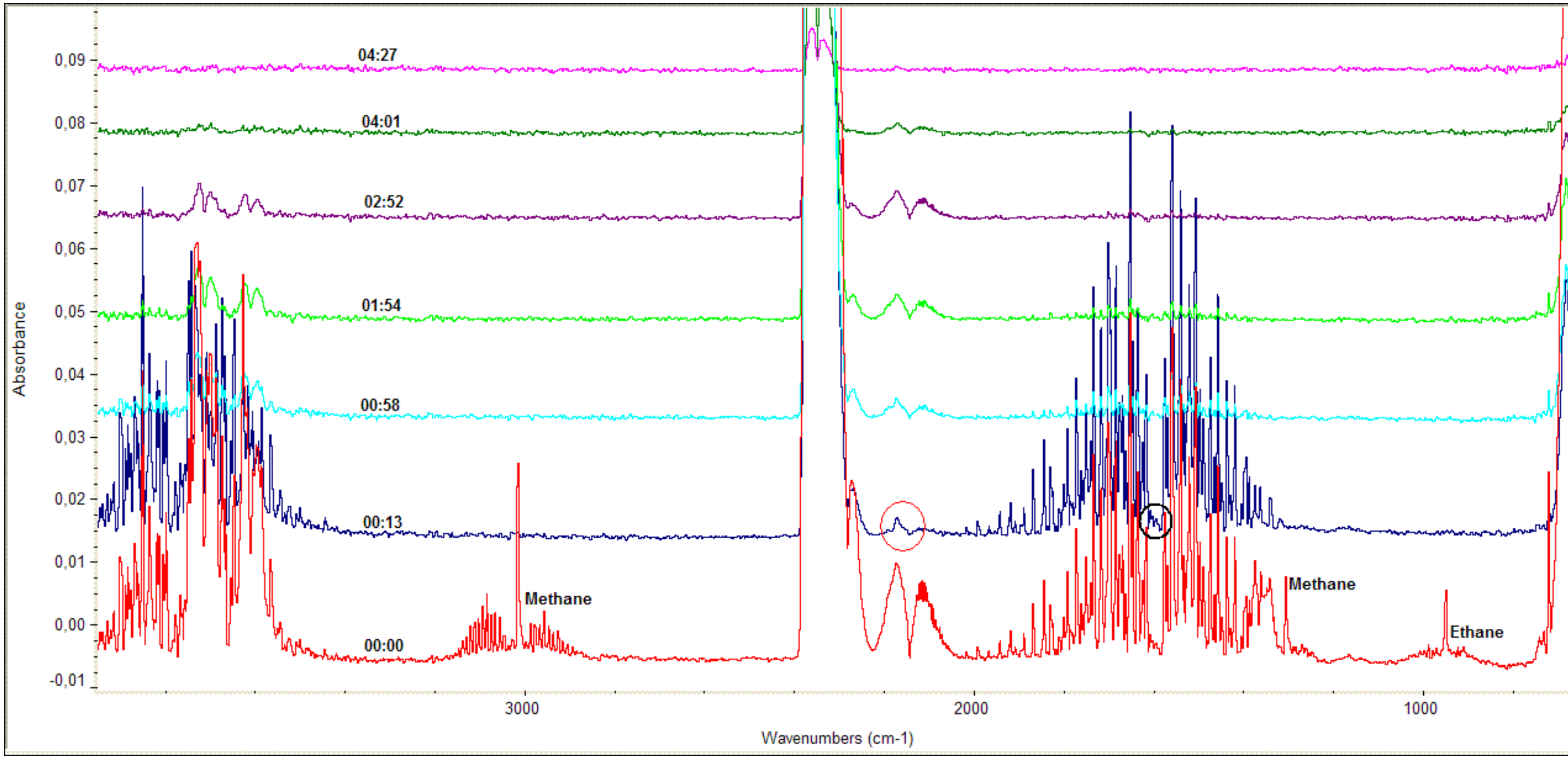
Single Particle – Louisiana Lignite

FTIR Spectra at Various Reaction Times

Oxidizer: Air



Evolution of some species appears to be somewhat reduced in combustion with air

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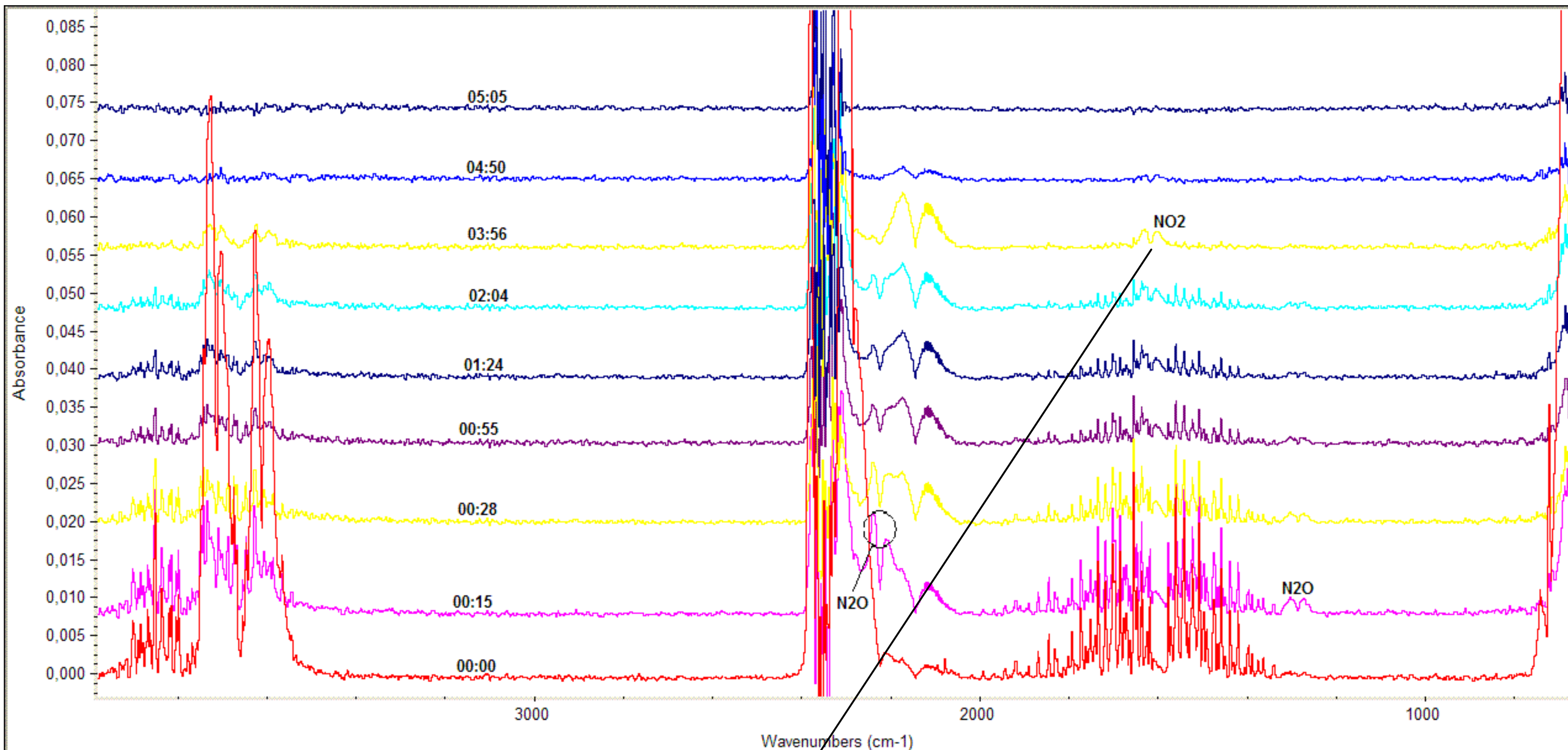
Single Particle - Char (PAN-6)

FTIR Spectra at Various Reaction Times

Oxidizer Composition: 50% O_2 - 50% CO_2



Possibility of very stable char N complex ⇒ XPS for identification

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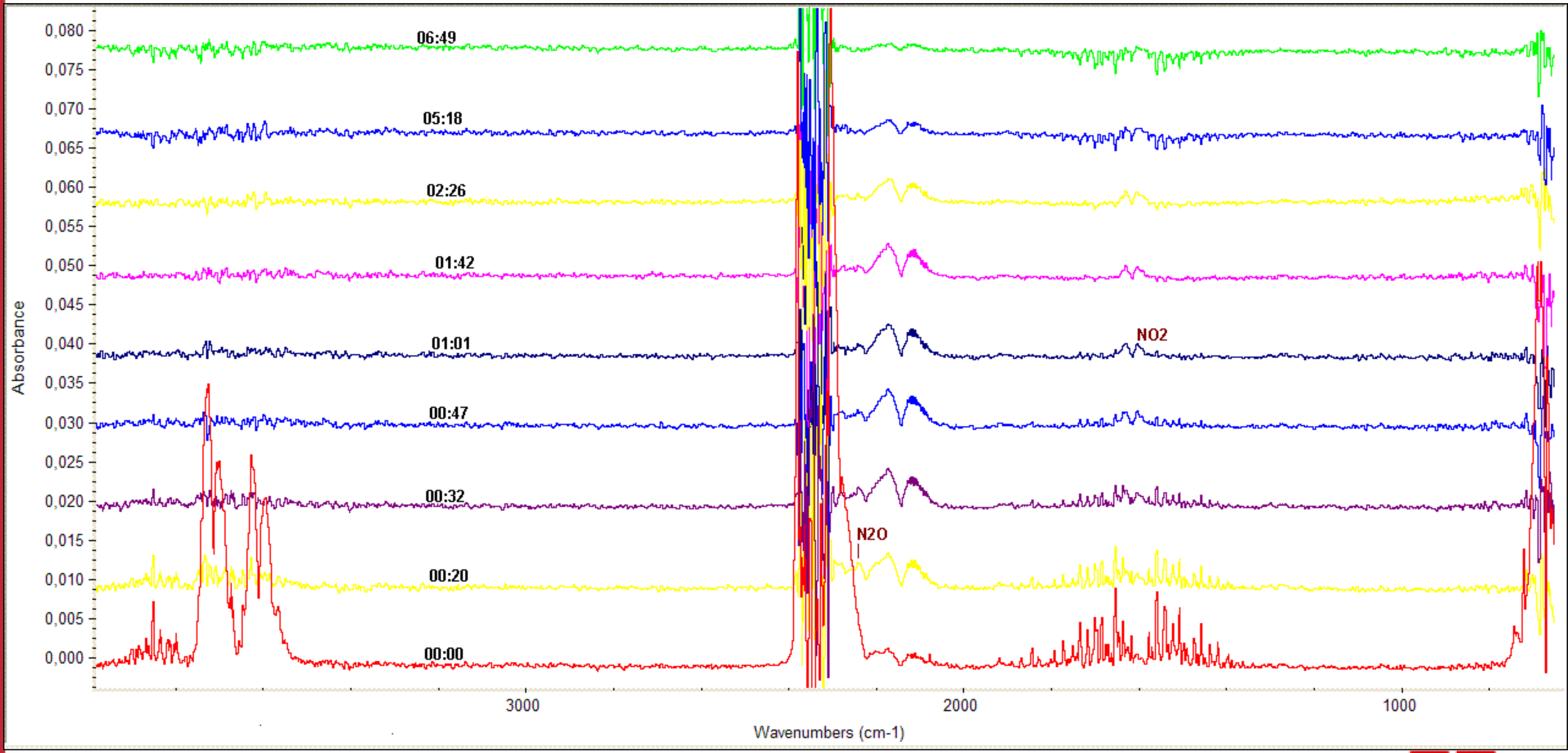
Single Particle - Char (PAN-6)

FTIR Spectra at Various Reaction Times

Oxidizer Composition: 25% O_2 - 75% CO_2



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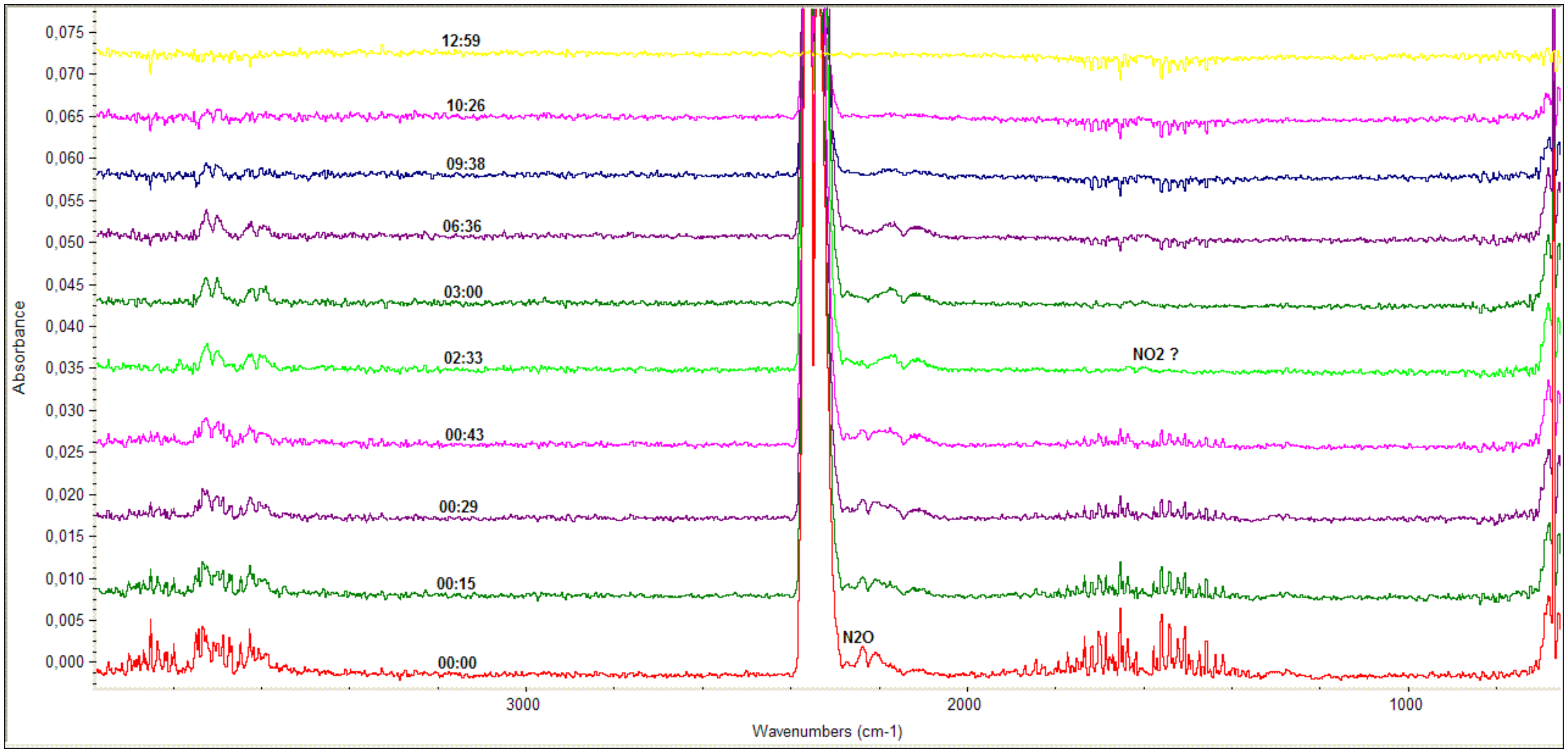
Single Particle - Char (PAN-6)

FTIR Spectra at Various Reaction Times

Oxidizer: Air



Low evolution of NO_2 and N_2O.

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Summary of Preliminary Experimental Results

- Preliminary results show important differences in the FTIR spectra of gas phase
  - Over time as particle burns out
  - Between air and different O_2, CO_2 concentrations
- Next steps
  - Complete characterization/identification of gas-phase FTIR spectra
  - Run matrix with different O_2 concentrations and either CO_2 or N_2 to identify impact of CO_2
    - Coals and model char
    - Analyze gas phase FTIR spectra
    - Analysis of solids (FTIR, XPS) for N functionalities at different times during reaction

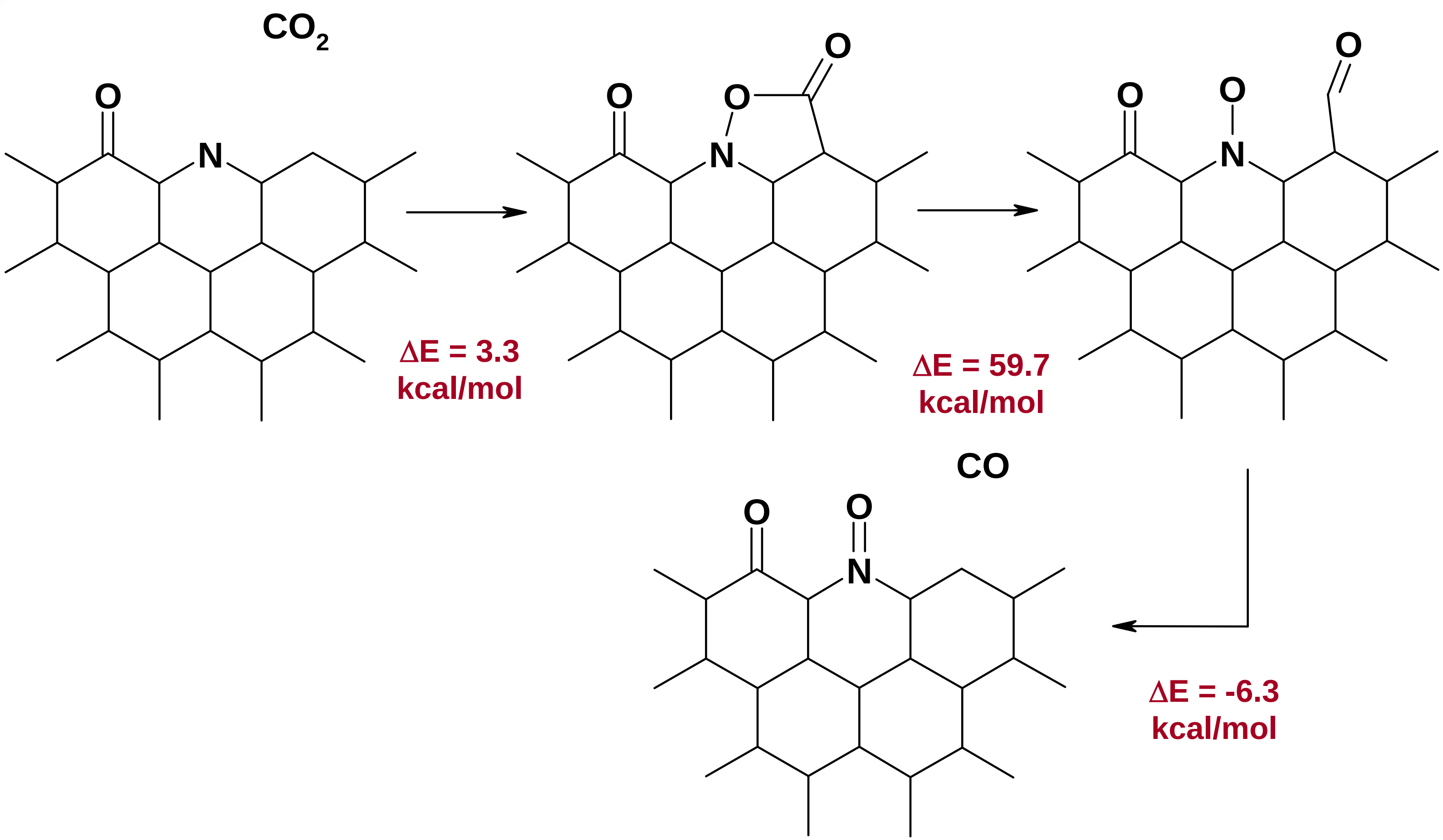
Preliminary Computational Results

Computational Methodology

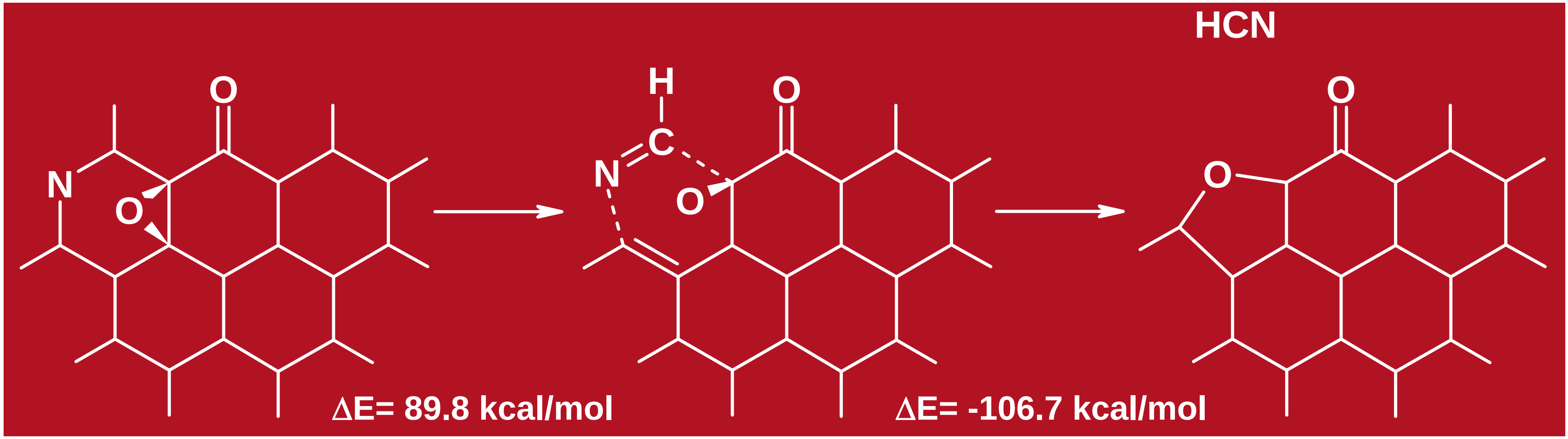
Package:	Gaussian 03
Char model:	Five condensed rings saturated with hydrogen
Theory level:	DFT
	Density Functional Theory
Basis set:	6311-G(d,p)

CO_2-N_{char} Interactions

$CO_2 + C(N) + C^* \rightarrow C(NO) + C(CO) \rightarrow CO + C^* + N(O)$



Precursor Formation: HCN



C-C bond is weakened by 30 % due to the presence of epoxy groups

High oxygen concentration ⇒ Facilitate formation of precursors

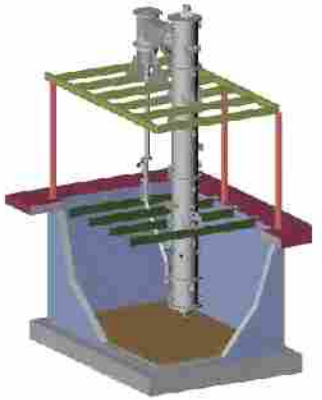
Initial Findings

- It is important to consider the interaction between recycled CO_2 and char N complexes, since this can modify the mechanism for char N conversion
- It is possible that decomposition of char N complexes will be facilitated by oxy-combustion systems due to formation of high amounts of surface oxygen complexes that promote char decomposition.
  - Can facilitate lower overall NOx emissions due to reduction in char N levels entering burnout zone in staged combustion (based on previous UofU data)

Pilot-Scale Oxycoal Circulating Fluidized Bed (CFB) Experiments

Pilot-Scale (300 kW) Experiments

– Specific Tasks:
- Modification of existing CFB facility for oxy-coal firing
- Development of particle concentration measurement capability
- Experiments
  – Detailed measurements will be made for use in model validation of DOE MFIX model for CFB's
  – Specific oxycoal experiments under Praxair support to investigate various operating parameters



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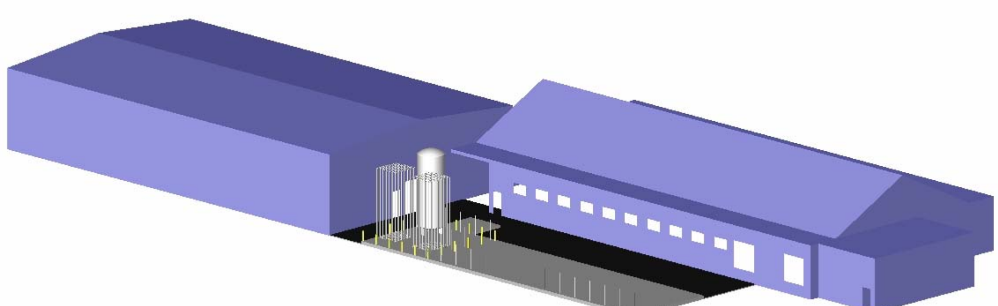
Status of Pilot-Scale Efforts

- Currently making modifications to pilot unit for oxyfiring with coal
  - Redesign of distributor plate/materials
  - Oxygen lines – plumbing, safety, control systems
  - FGR system, baghouse
- Anticipated completion April 2008
- Curently evaluating several methodologies for mapping particle concentration
  - Acoustic methods
  - Capacitance methods

Addressing the Oxygen Supply

- Need to provide O_2 supply for
  - oxy-coal combustion programs
  - coal gasification programs
- Praxair supplying the tank, delivery system and O_2 for oxycoal studies
  - Capabilities
    - 6000 gallon storage
    - Max. delivery: 150 SCFM O_2
- Status
  - Storage site (pad) currently under construction
  - Anticipate completion of tank installation by end of Mar. 2008



Concluding Comments

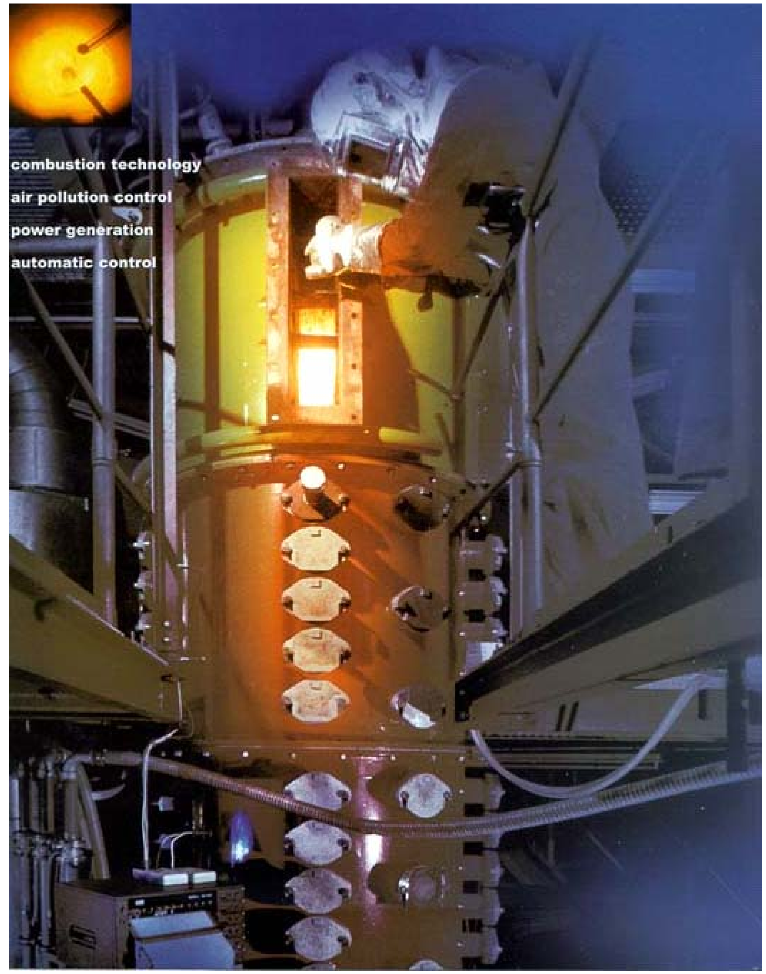
- Preliminary fundamental results indicate need for further investigation on
  - interactions between Char N and CO_2
  - effect of O_2 level on N species release
- Pilot-scale experimentation to commence late Spring of 2008
  - Optimization of oxycoal firing in CFB
  - Model validation data
  - Development/adaptation of novel techniques for particle concentration measurement

3rd Workshop
IEAGHG International Oxy-Combustion Network
Yokohama, Japan
5th and 6th March 2008

Impact of Combustion Conditions on Emission Formation (SO_2, NO_X) and fly ash

Patrick Mönckert, Bhupesh Dhungel, René Kull
Jörg Maier

Maier@ivd.uni-stuttgart.de



Topics of Presentation, R&D Topics at IVD

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- Fuel characterization (electrical heated pf reactors)
  - Combustion
    - Rank of coal (bituminous, lignite…)
    - Emission formation, ricirculation (NO_X, SO_2, H_2S, CO…
    - Char burnout and fly ash formation
  - Pyrolysis under CO_2 and N_2 atmosphere
    - Volatile release and char formation/reactivity
- Technical scale combustion tests ($0.5MW_{th}$)
  - Combustion and emission behavior, slagging, fouling, corrosion, SO_3,, acid dew point
  - Component development and test (burner…)
  - Plant handling and operation, safty requirements
- Model development and combustion simulation (AIOLOS)

Parameter Study on Emission Formation

(SO_2, H_2S)

electrically heated reactor (20kW)

Analysis of the Coals Used

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Coals	LHV [%,ar]	Moist. [%,ar]	Ash [%, wf]	Vol. [%, waf]	Cfix [%, waf]	C [%, waf]	H [%, waf]	N [%, waf]	S [%, waf]	O [by diff]	Ca in ash [%]	Ca/S [mol. Ratio]
Klein Kopje	24932	3.60	**19.29**	**27.76**	72.24	83.93	4.50	1.67	**0.72**	9.18	**5.8**	**2.98**
Lausitz	21412	10.20	**5.46**	57.36	42.64	66.78	5.26	0.65	**0.85 (0.36)**	26.5	**17.0**	**3.17**
Rhenish	20965	11.50	**4.07**	54.18	45.82	67.96	7.68	0.73	**<0.3**	23.6	**26.3**	**3.96**
Ensdorf	30955	2.42	**7.47**	**37.21**	61.90	74.85	5.05	1.59	**0.83**	17.7	**7.55**	**1.03**

	Klein Kopje Coal	**Lausitz Coal**	**Rhenish Coal**	**Ensdorf Coal**
D_{10} [µm]	4.83	7.46	10.83	5.79
D_{50} [µm]	28.05	47.91	93.07	23.66
D_{90} [µm]	72.68	142.54	264.65	92.25

Set-up and description of 20 kW once through furnace

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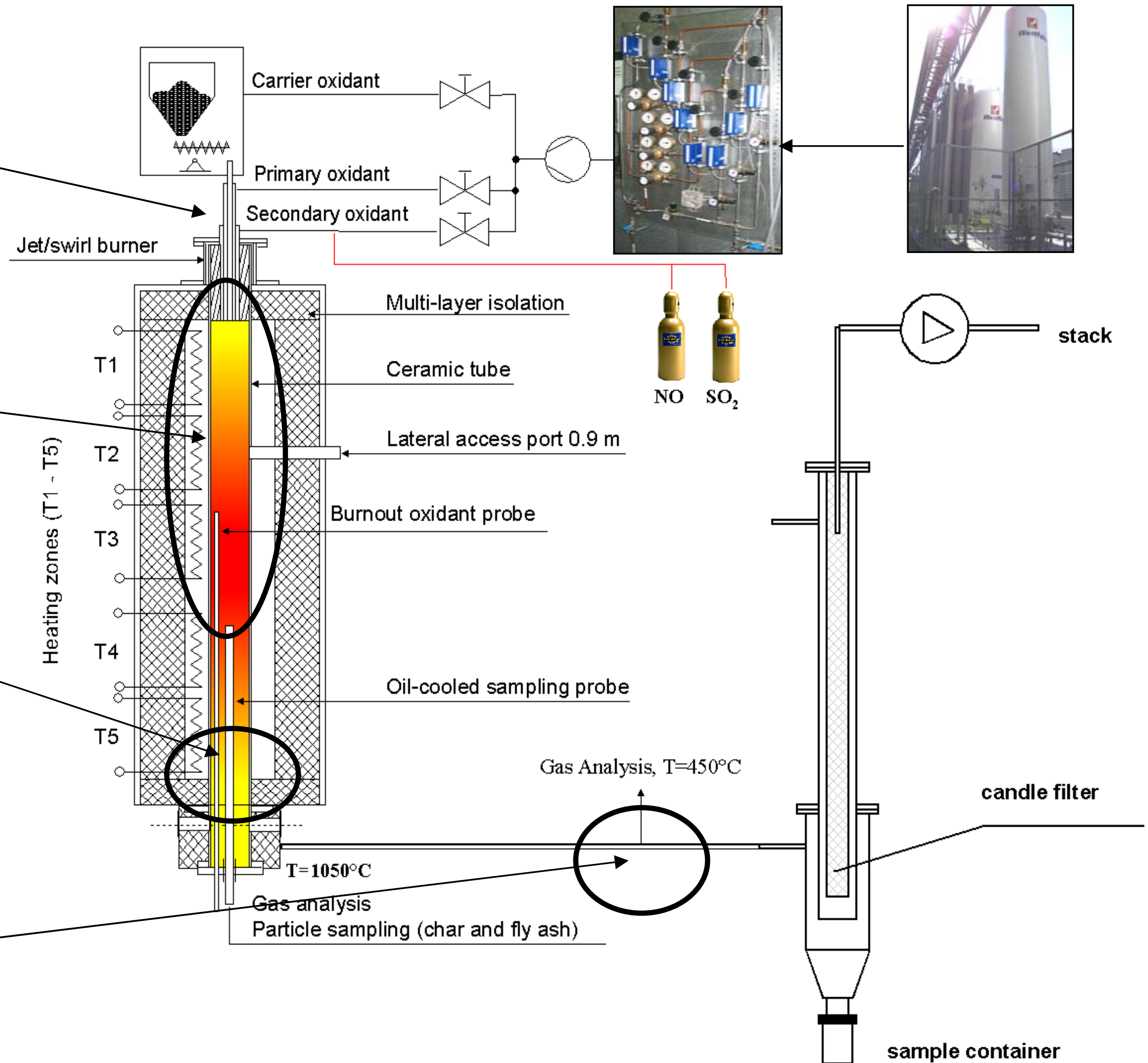
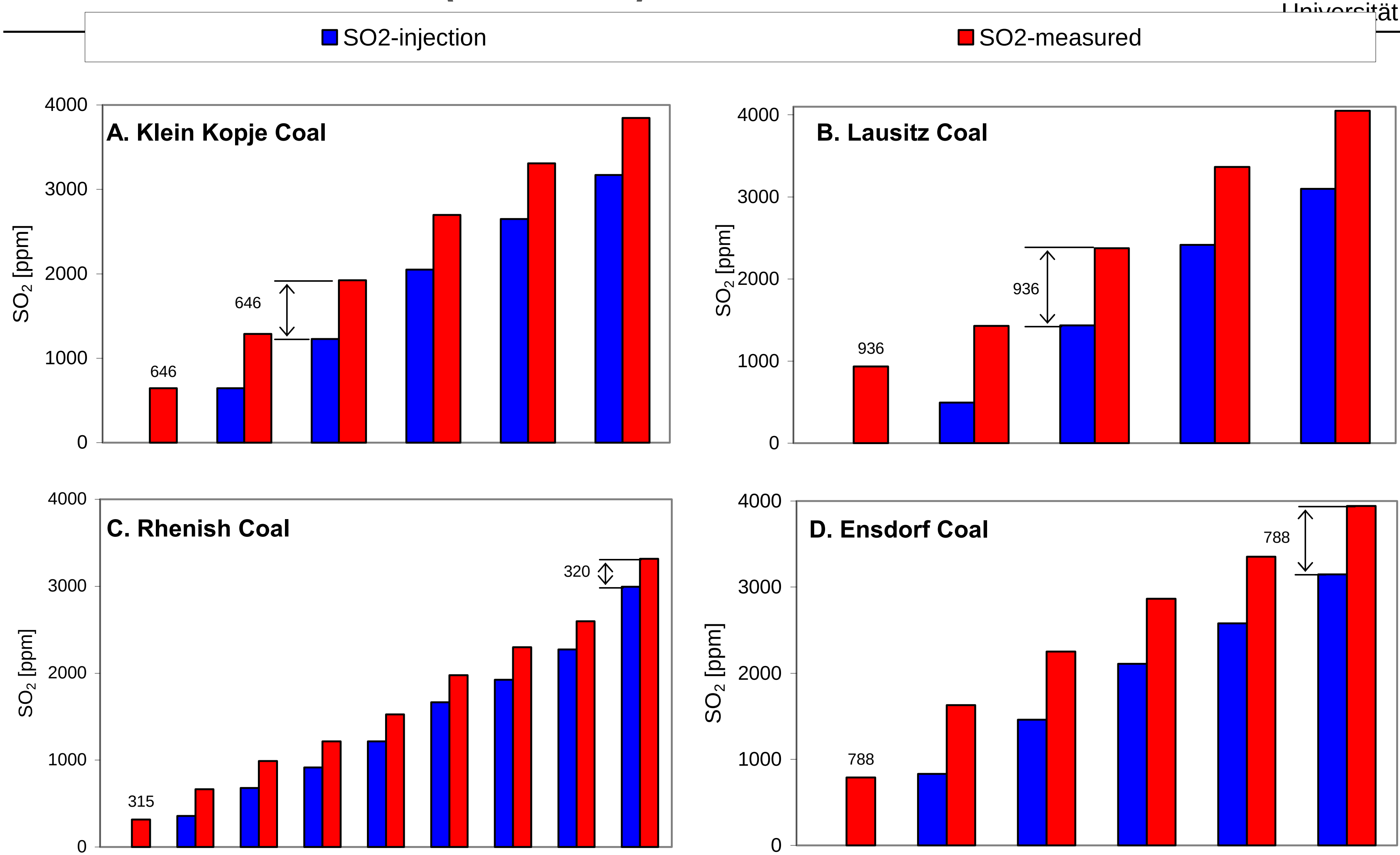
- ➢SO_2 Injection: up to 3000 ppm via the secondary stream of the burner
- ➢In-flame measurements H_2S/SO_2, staged/unstaged
- ➢SO_2 measurements outlet rediative section T=1150°C
- ➢SO_2 measurements outlet of convective section T= 450°C



Test Results:

- **SO_2 emission** at the **outlet** of the **rediative section** (1150°C) by SO_2 injection up to 3000ppm
- **SO_2 captured along the convective section** (1150°C down to 450°C) by SO_2 injection up to 3000ppm

Impact of SO_2 injection at the outlet of the radiative section (1150°C), OF27



➤Negligible reduction of recycled SO_2 in the high temperature, radiative section of the furnace.

SO_2 captured along the convective part (down to 450°C) by different inlet concentrations

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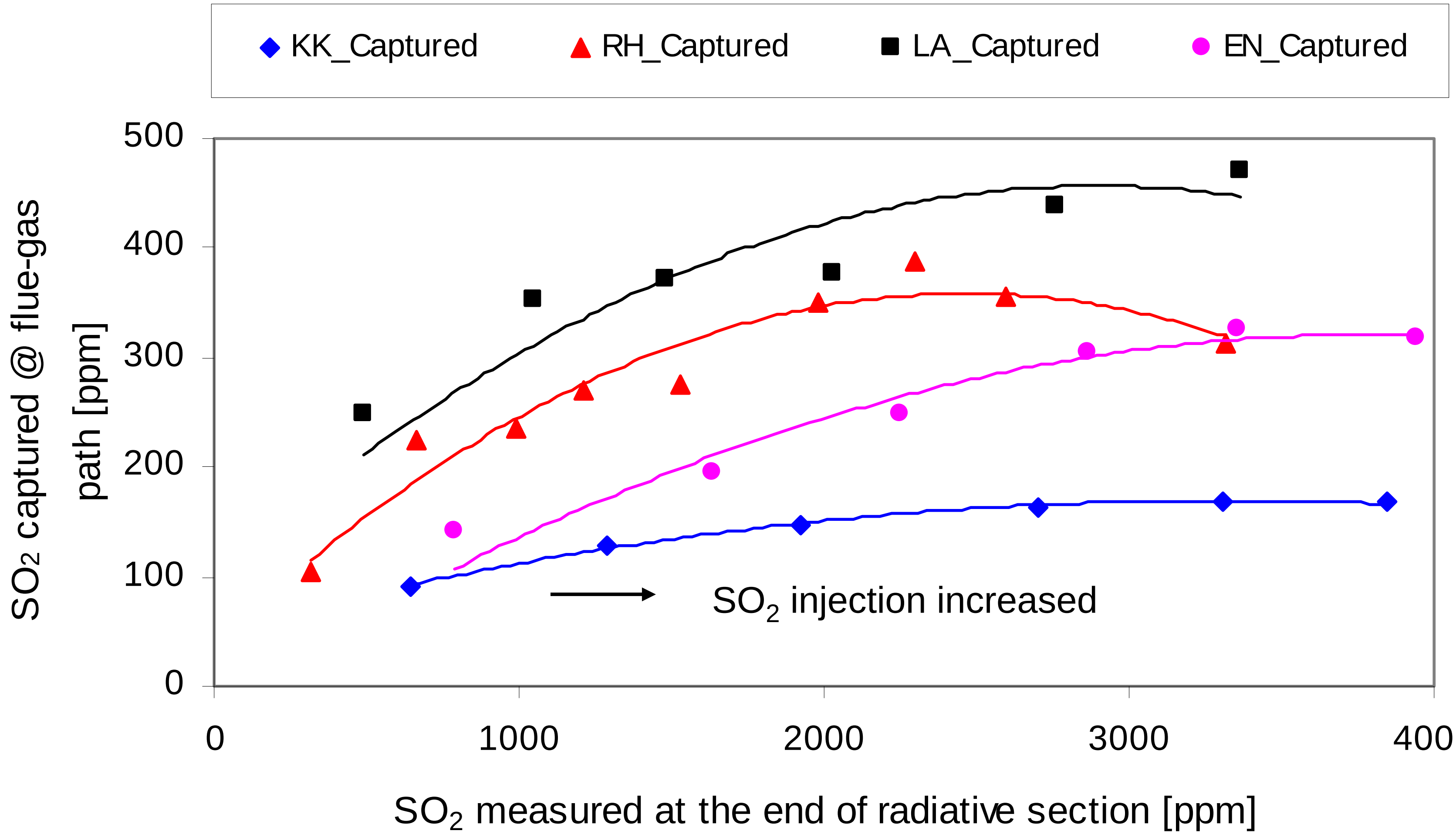

Oxy-fuel 27 % O_2

In-flame measurements of staged flames with focus on SO_2 and H_2S with and without injection of 3000ppm SO_2

H_2S formation: Impact of SO_2 accumulation (λ_1=0.75)

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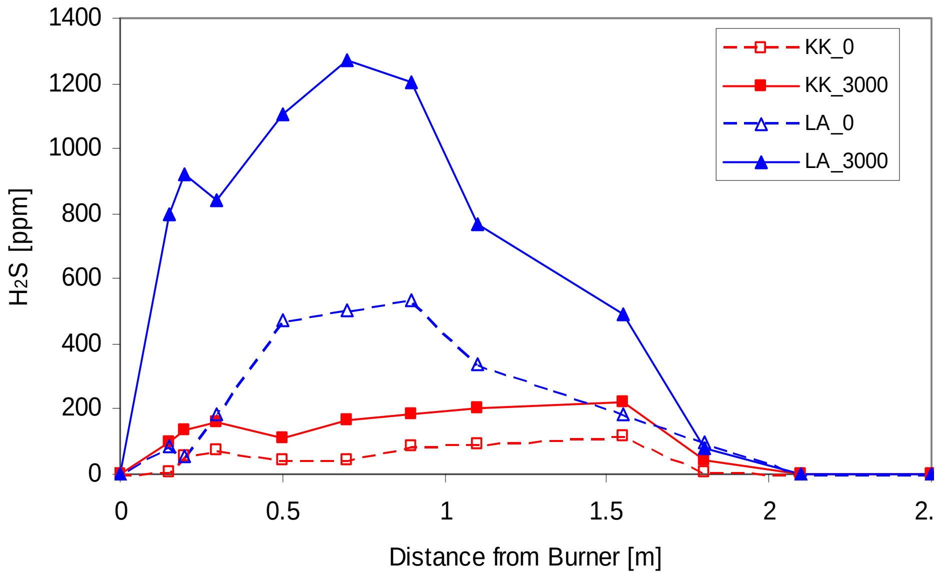
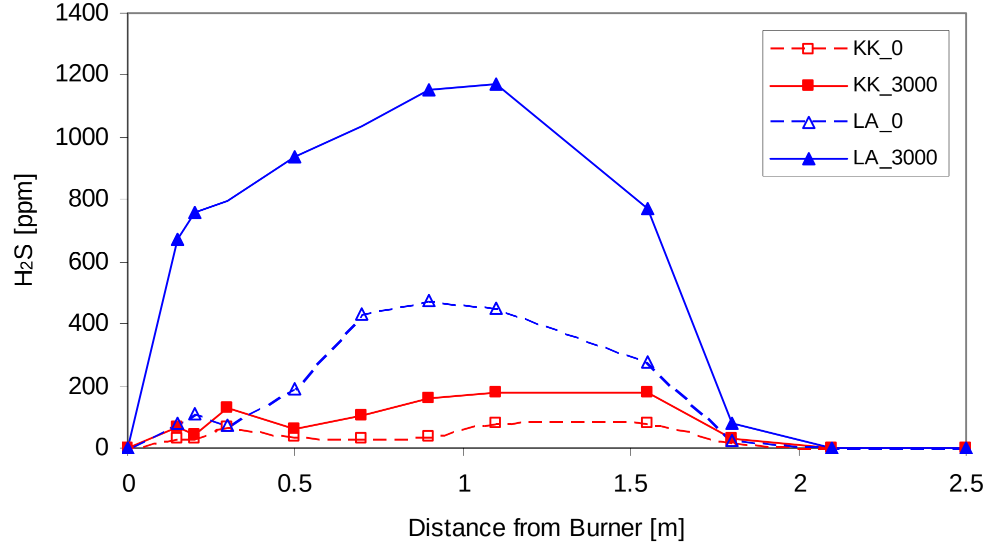


OF27



Air-Blown

Higher SO_2 concentrations (3000ppm) in the furnace results in at least 2 times more H_2S formation in the sub-stoichiometric region➔ H_2S induced corrosion.

Impact of coal property on H_2S formation (λ_1=0.75, T_1~3 Sec)

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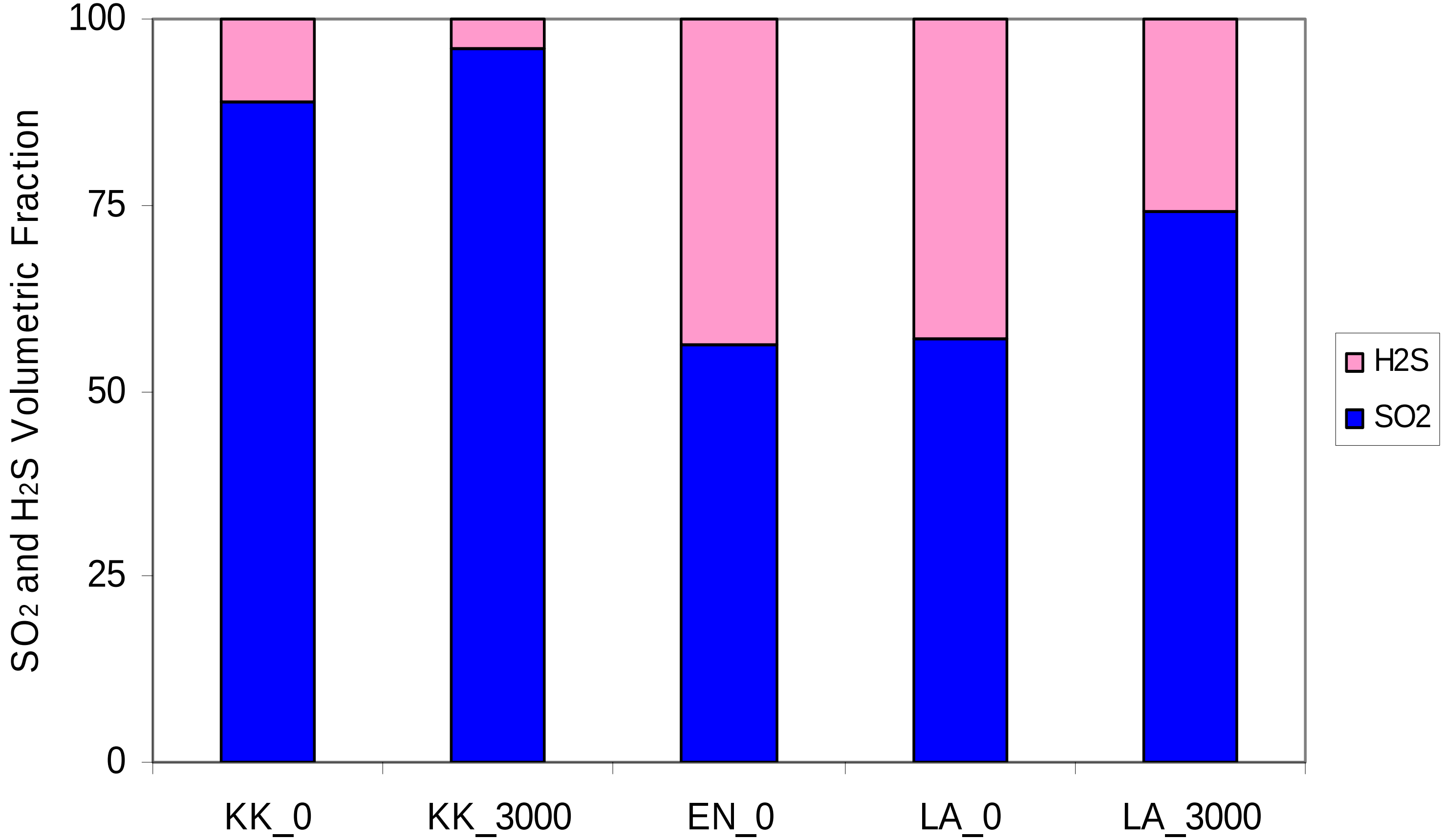

Volumetric percentage of H_2S and SO_2 in the sub-stoichmetric furnace section, Oxyfuel 27 % O_2

Results of Parameter Study (SO_2/H_2S)

- H_2S concentrations in the furnace can significant increased under oxyfuel conditions,
- Volumetric percentage of H_2S in the furnace decreases by higher SO_2 input concentrations
- H_2S formation seems to be influenced by volatile content of the coal and may other parameters: mineral composition etc.
- conversion of Sulphur to SO_2 close to 100% at the outlet of the rediative section for the investigated coals and atmospheres
- calcium rich coals show a clear tendency to capture additional Sulphur with increasing SO_2 concentration (Oxyfuel conditions), this correlates with increasing SO_3 concentrations of the fly ash

SO_3 measurements and acid dew point calculations in the flue gas duct of a 500kW facility

Oxyfuel facility (0.5 MWth) – SO_3 sampling

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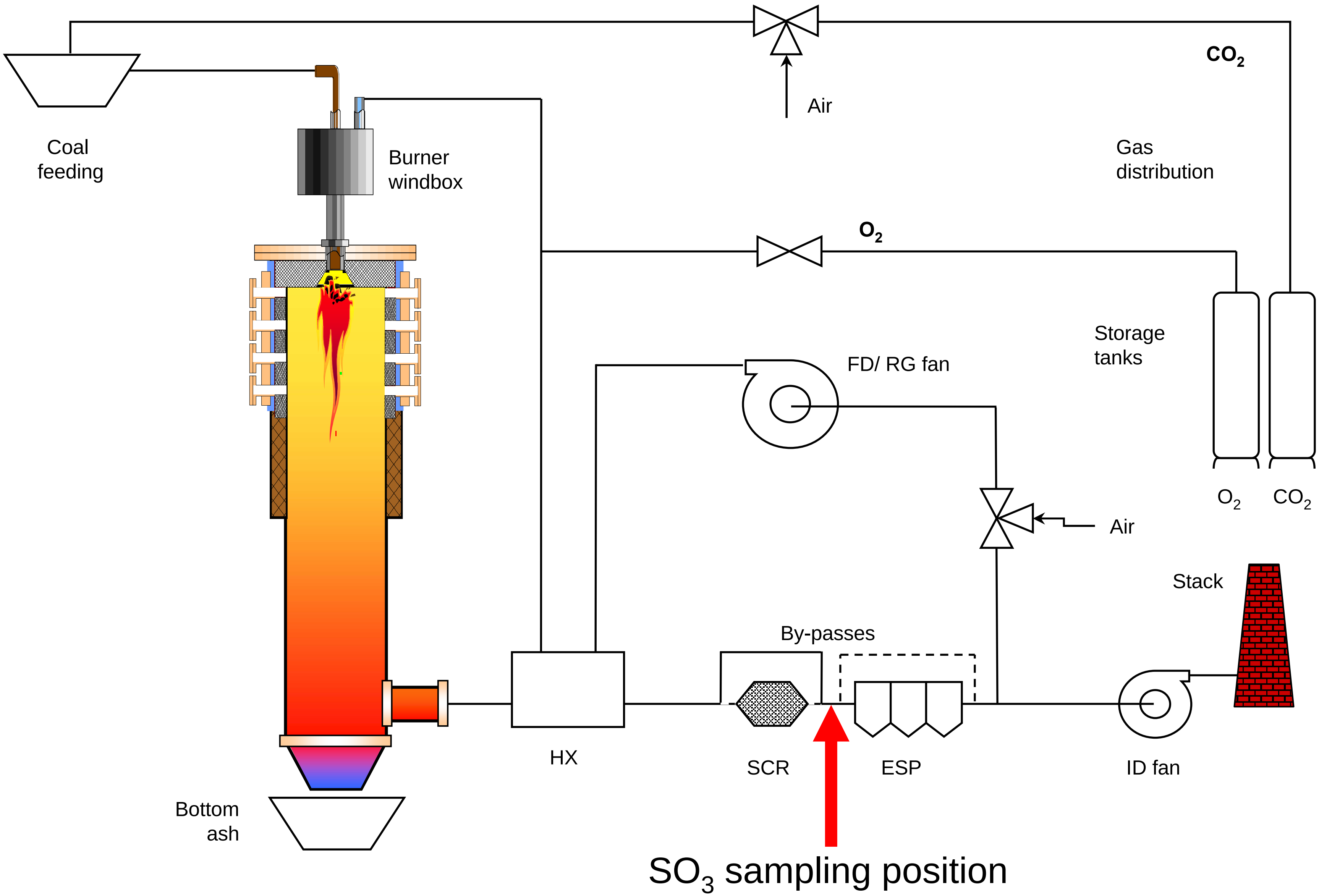

Measured SO_3 concentrations for Lausitz coal at AIR and OXYFUEL combustion conditions

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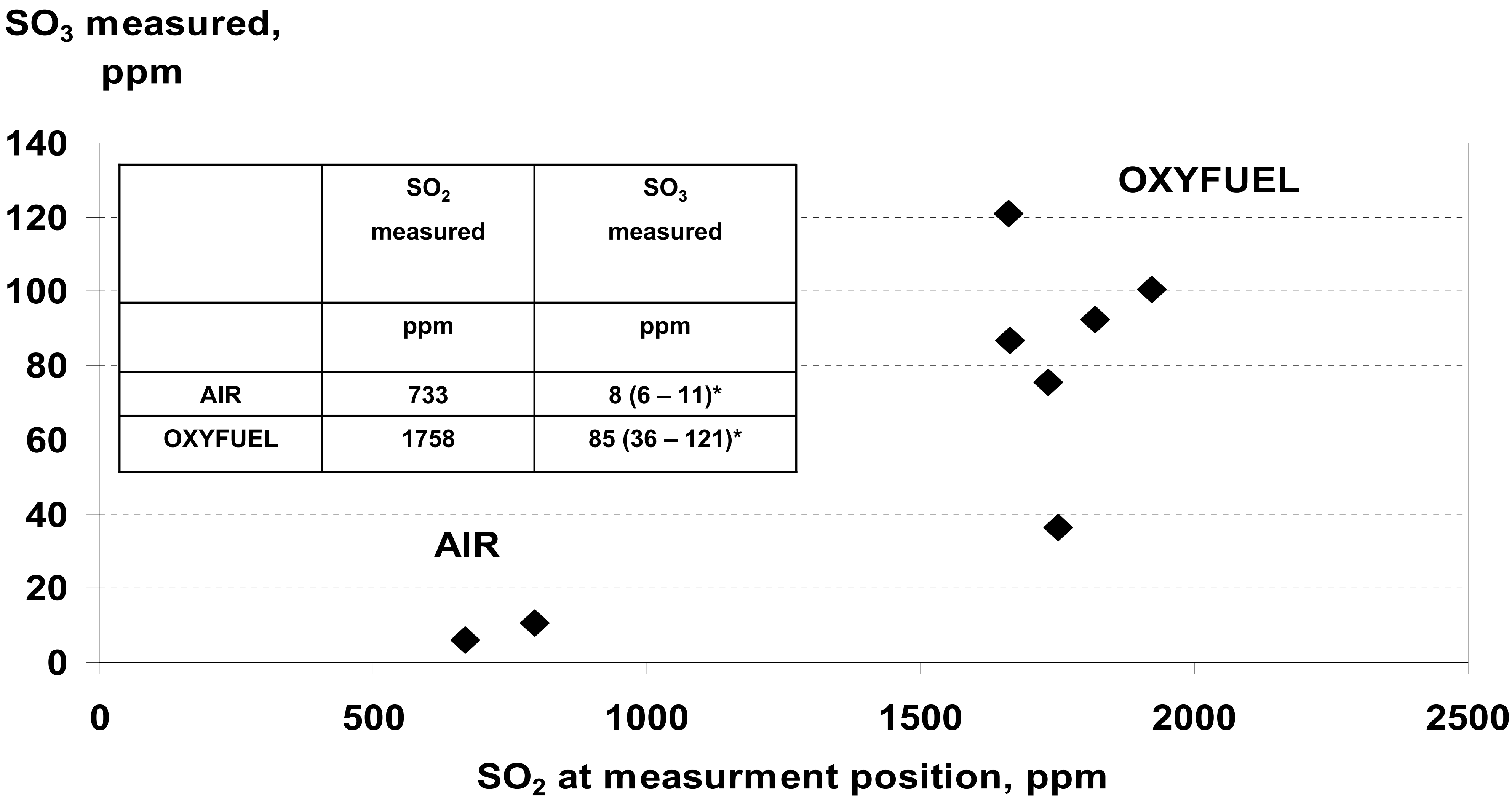

	SO_2 measured	SO_3 measured
	ppm	ppm
AIR	733	8 (6 – 11)*
OXYFUEL	1758	85 (36 – 121)*

* ... min. / max. value measured

Acid dew point T correlated with conversion rate of $SO_2 \rightarrow SO_3$

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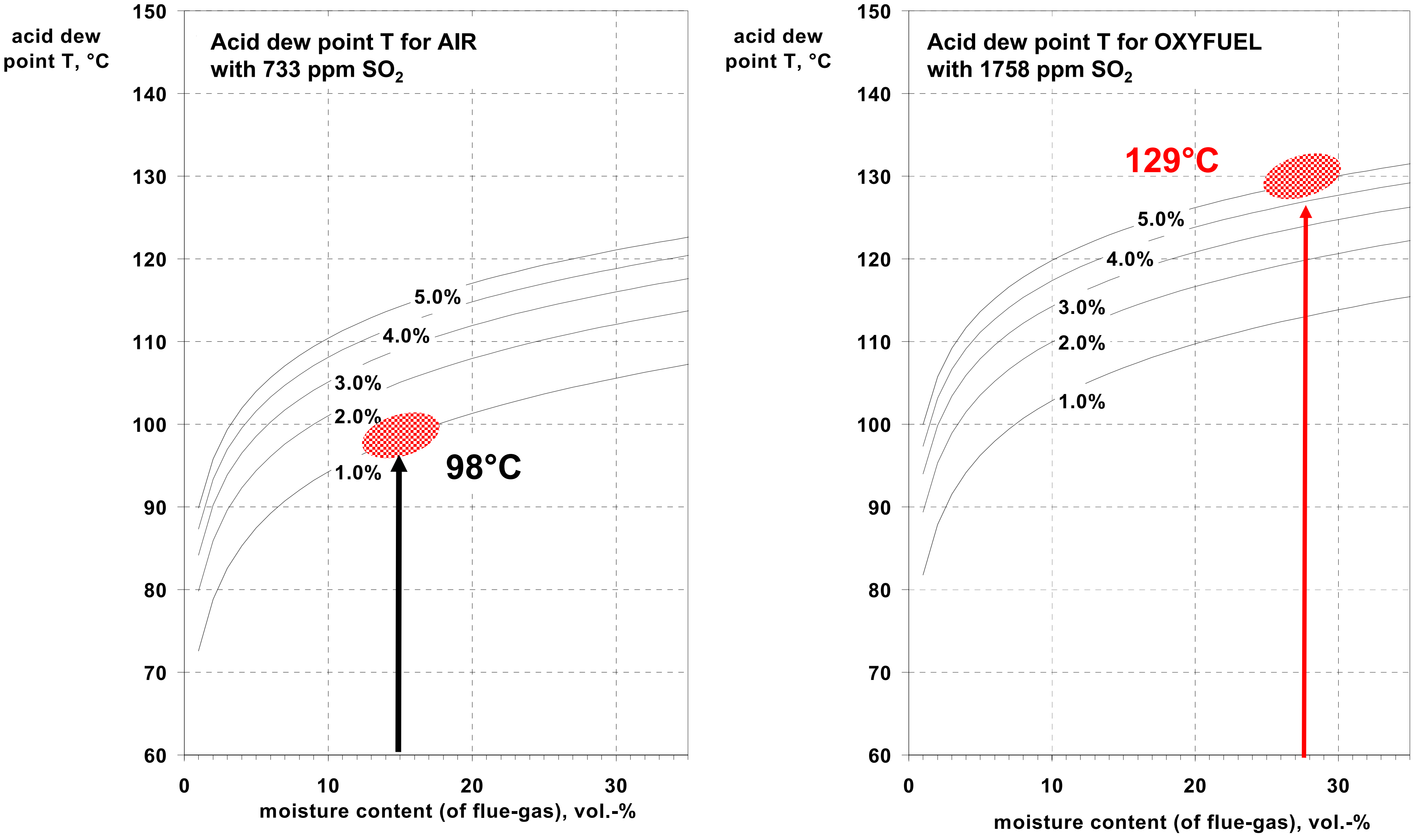

Desposits under oxyfuel conditions

Deposit-Sampling Probes (air/oxyfuel)

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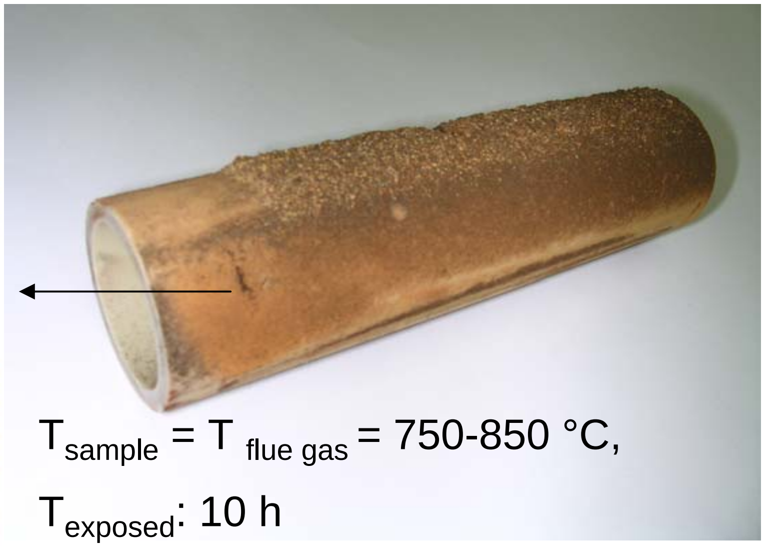
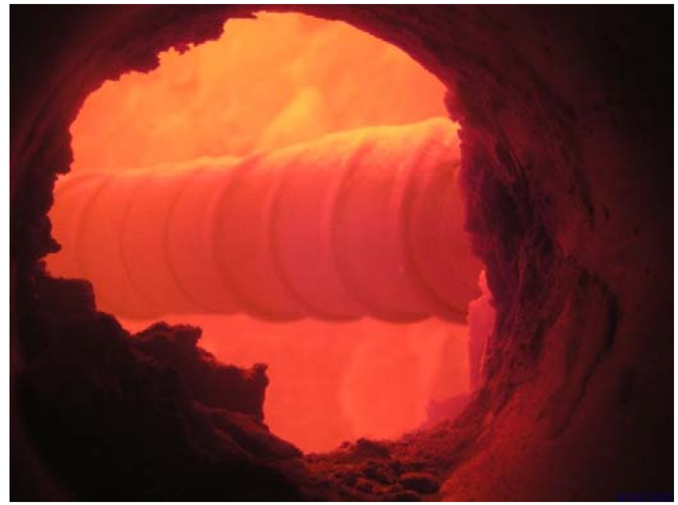
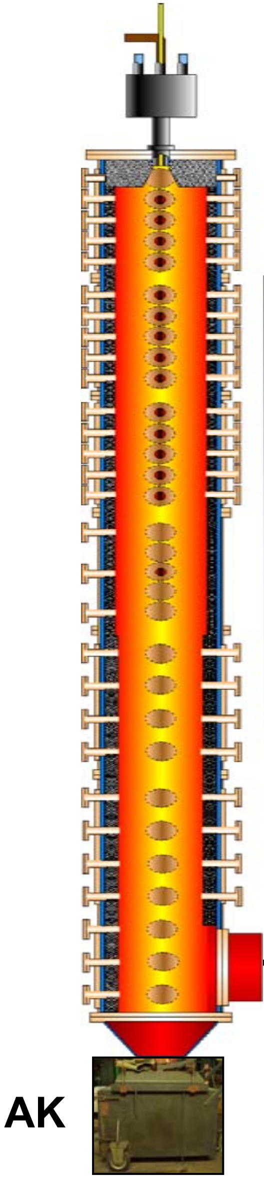
Un-cooled ceramic

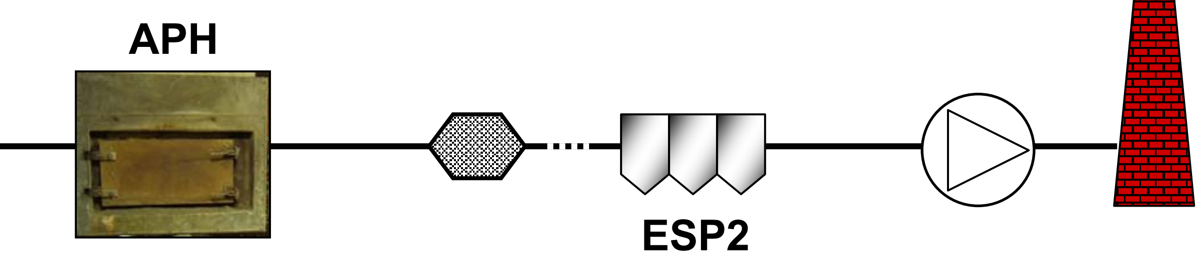


temperature controlled

(alloys 400-750°C)







SEM-BSE and SEM-MAP Ca-C

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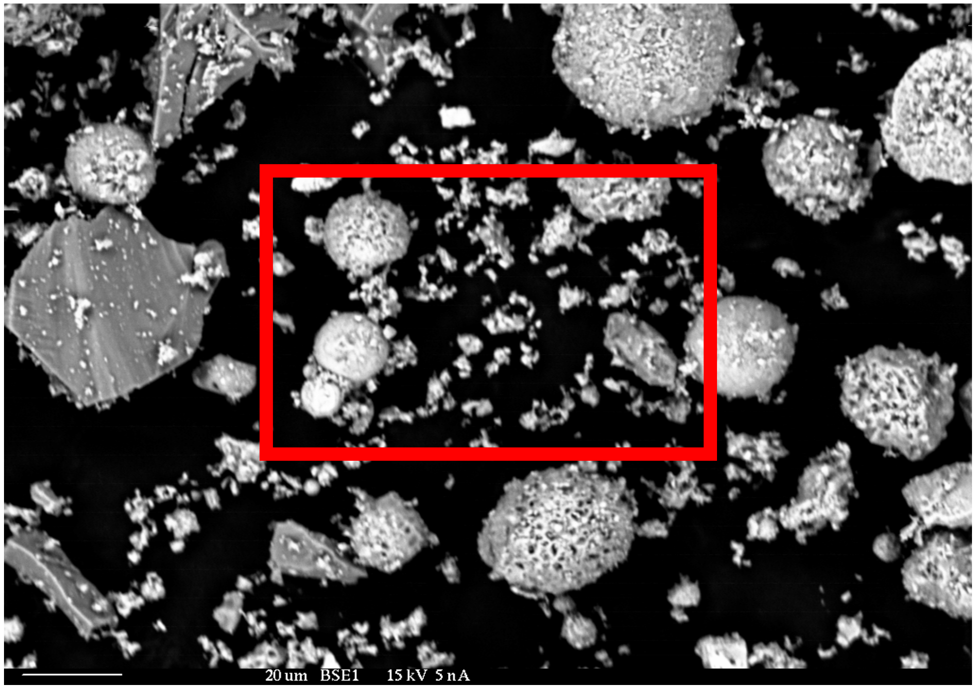

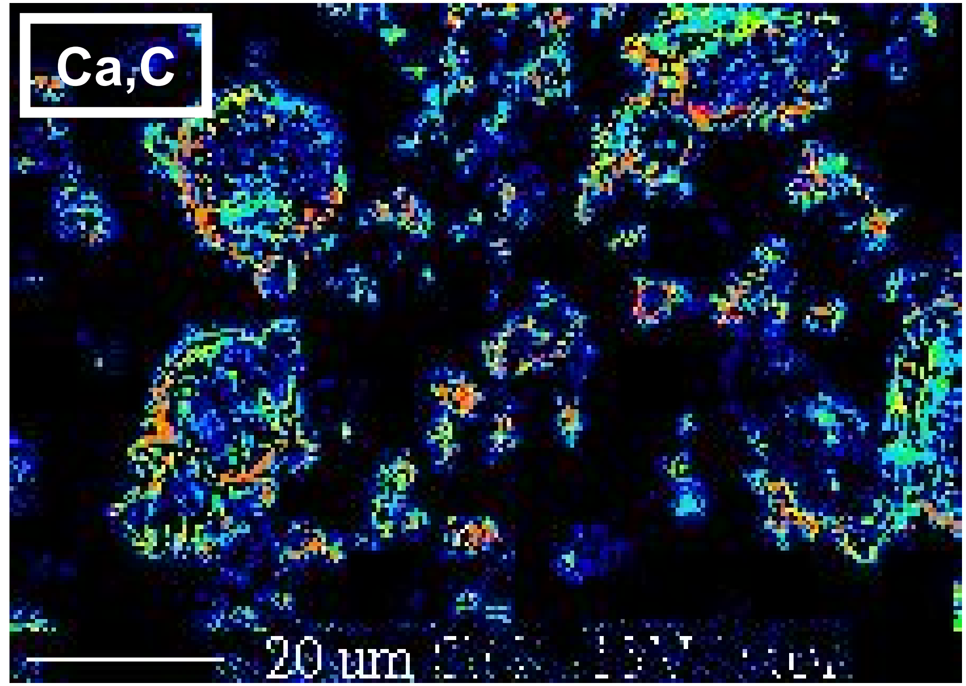

SEM-WDS/EDS-MAP: Al, Si, O and Ca, S, Fe

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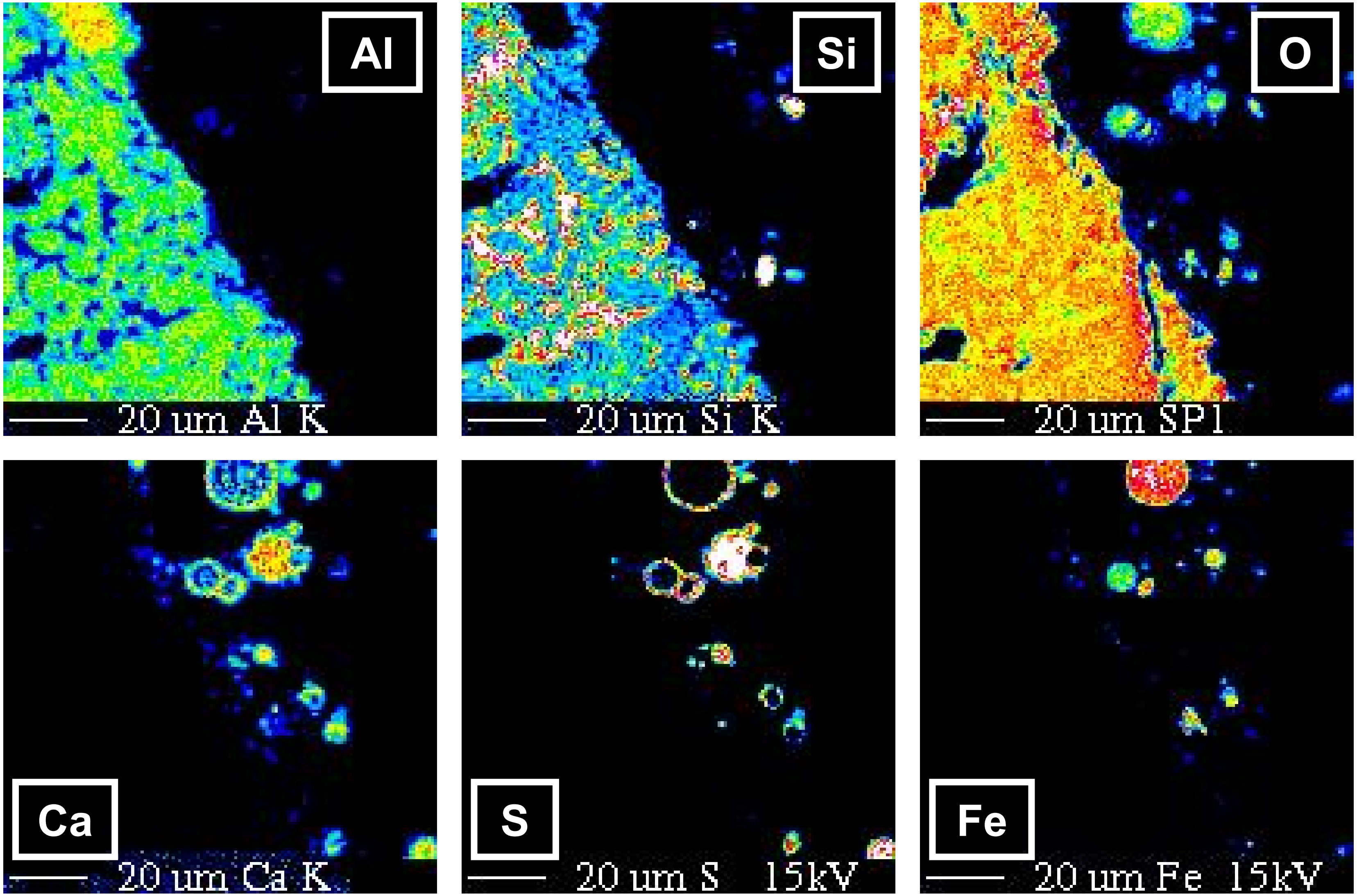
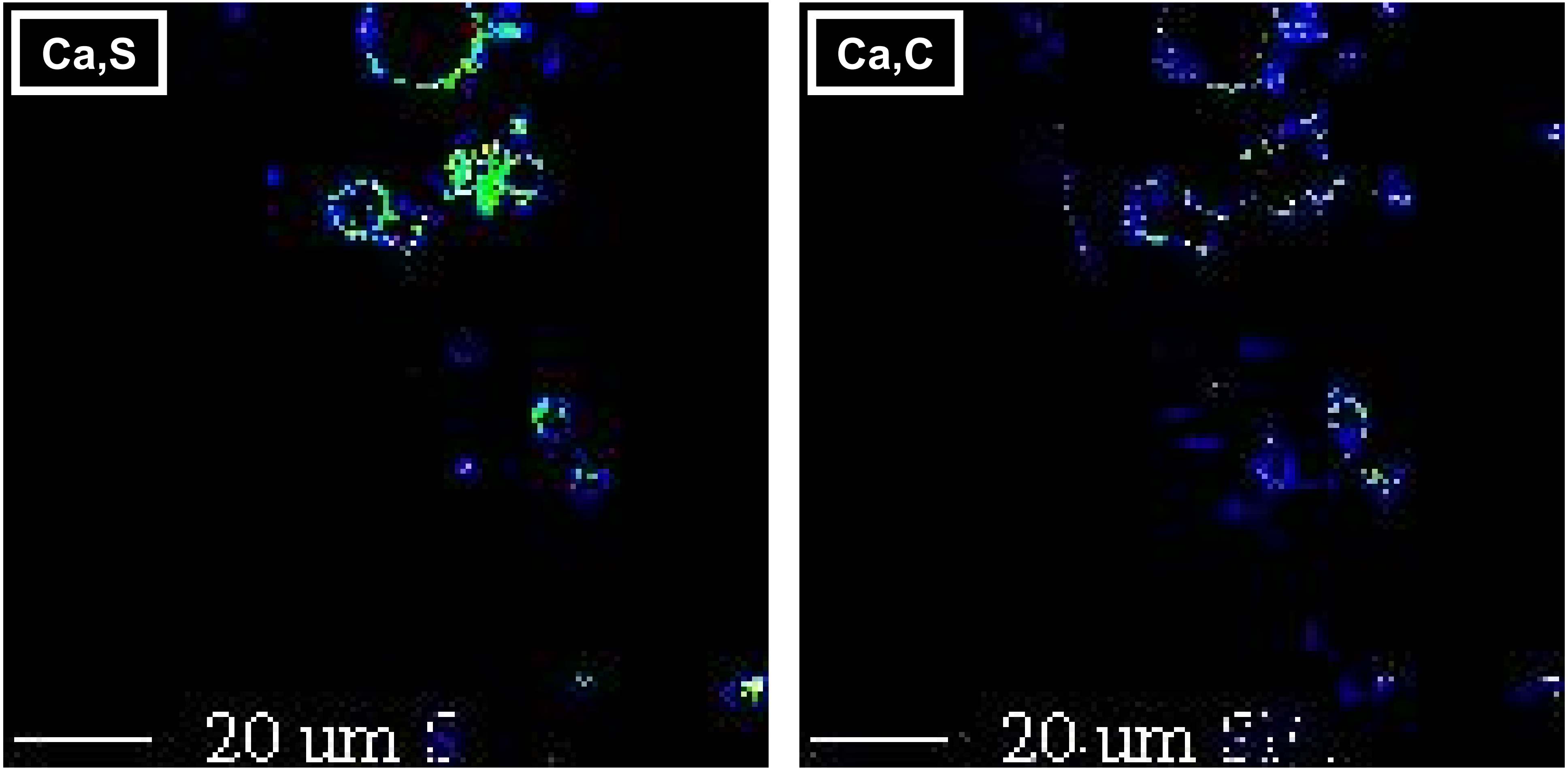


SEM-MAP: Ca,S / Ca,C



Results of the 500kW facility- SO_3 and Deposits

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- Clear tendencies that under Oxyfuel conditions the SO_3 concentration is increasing and also the acid dew point temperature
- Impact of Oxyfuel conditions on SO_2/SO_3 conversion rate needs further clarification
- Further measurements of SO_3 and acid dew point temperatures are required to minimize uncertainties (measurement device, measurement procedure, operational issues of plant etc.

- Indications that beside sulfatization carbonization on the particle surface of deposits occurs under Oxyfuel conditions
- Impact of carbonization on fouling and corrosion in the convective section of the boiler needs further testing

Ongoing/Future R&D Topics at IVD

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- Experimental Oxyfuel combustion topics:
  - Rank of coal (bituminous, lignite…)
  - Slagging, Fouling, (impact of higher SO_2, H_2S, CO_2, HCl etc.
  - Corrosion high-low temperature (Deposits, HCl, SO_2, SO_3, H_2O…
  - Fly ash quality (EN 450 …)
  - Component development and test (burner, …)
  - Emissions (Hg, fine dust etc)
  - Flue gas cleaning (SCR, Additives…)

- Oxy-fuel: PF/CFB,
- Post combustion capture: Carbonate Looping (connected CFB/FB starts operation April 2008)
- Lime Enhanced Gasification: Hydrogen rich Syngas

SO_2/ SO_3 sampling and analysis procedure according to VDI (draft) guideline

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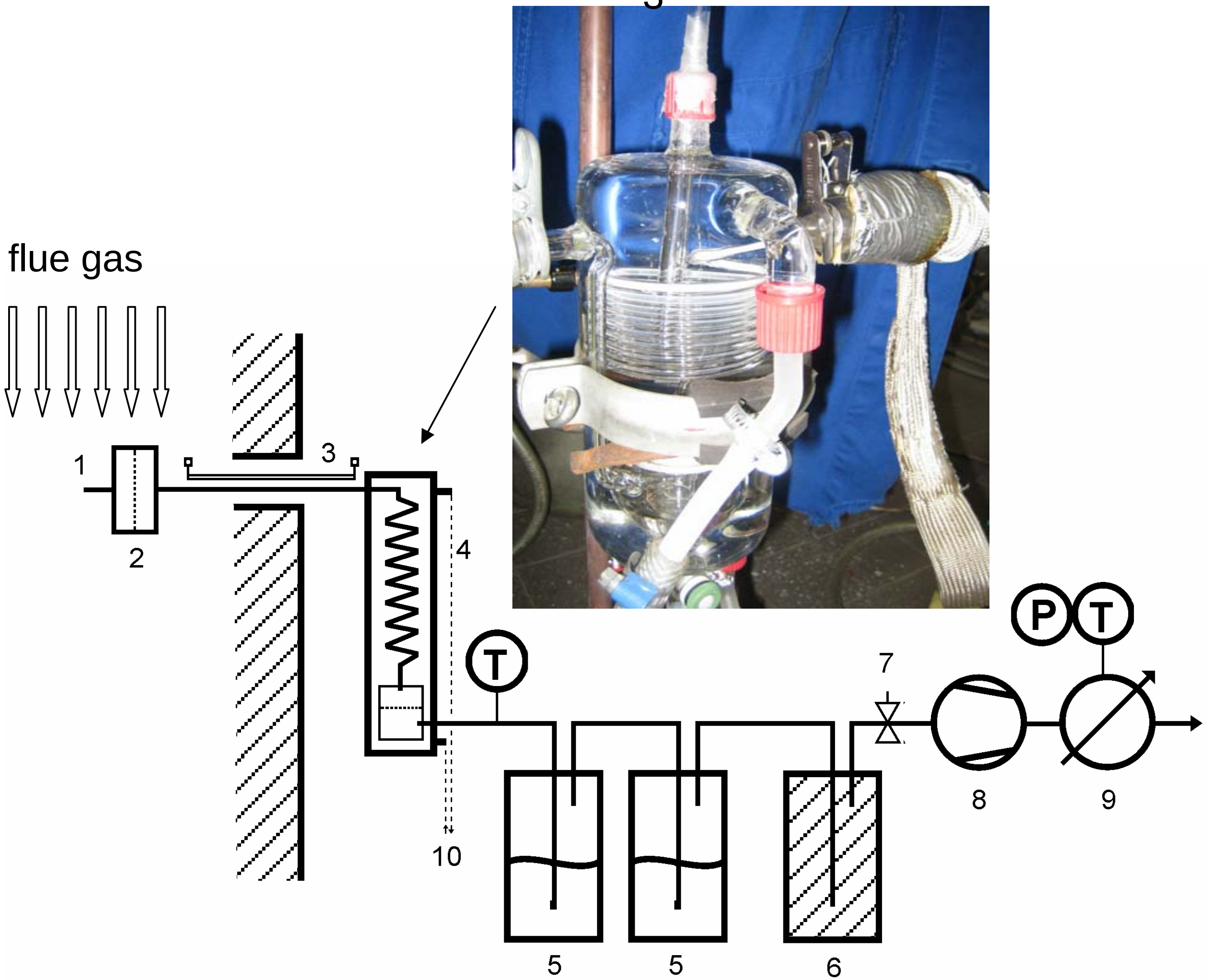
SO_3 Condenser



<u>Sampling equipment</u>

1 Sampling probe
2 Particle filter
3 Heating
4 SO_3 condenser and thermostat
5-6 SO_2 absorption vessels
7-9 Sampling pump

Efficiency Increase of the Oxyfuel Process by Waste Heat Recovery Considering the Effects of Flue Gas Treatment

Mathias Klostermann

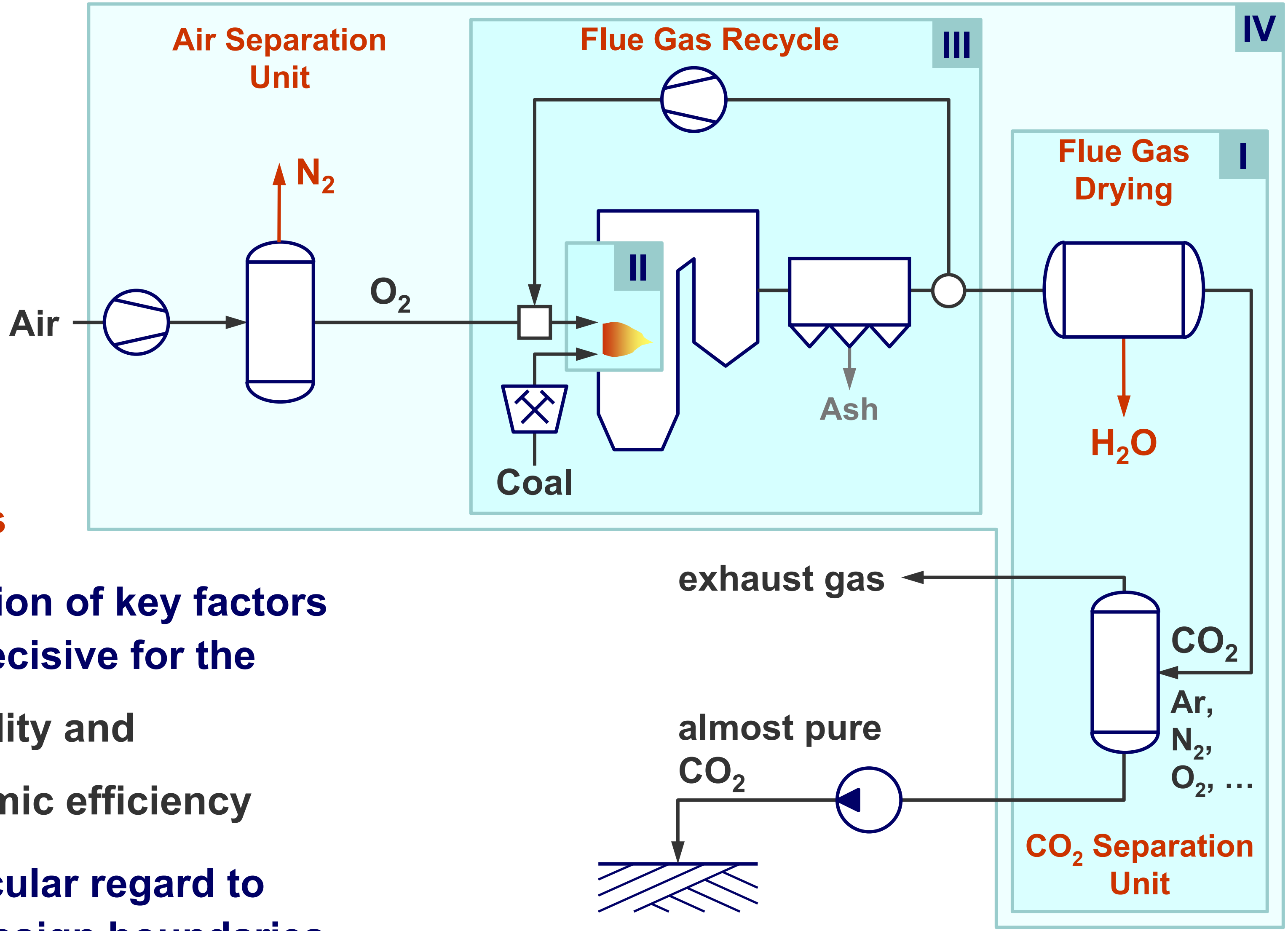
Institute of Energy Systems

Prof A Kather
C Hermsdorf
M Klostermann
K Mieske

TUHH
Technische Universität Hamburg-Harburg

IEAGHG International Oxy-Combustion Network - 3rd Workshop,

5th and 6th March 2008, Yokohama Japan

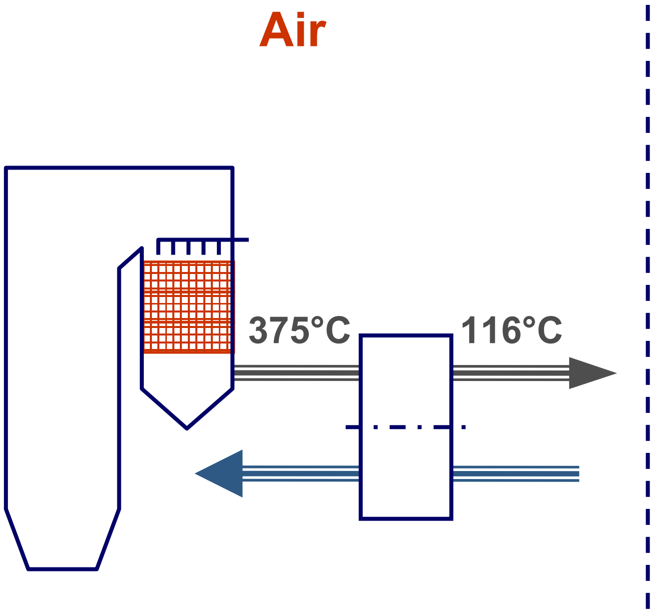


Objectives

Identification of key factors that are decisive for the

- feasibility and
- economic efficiency

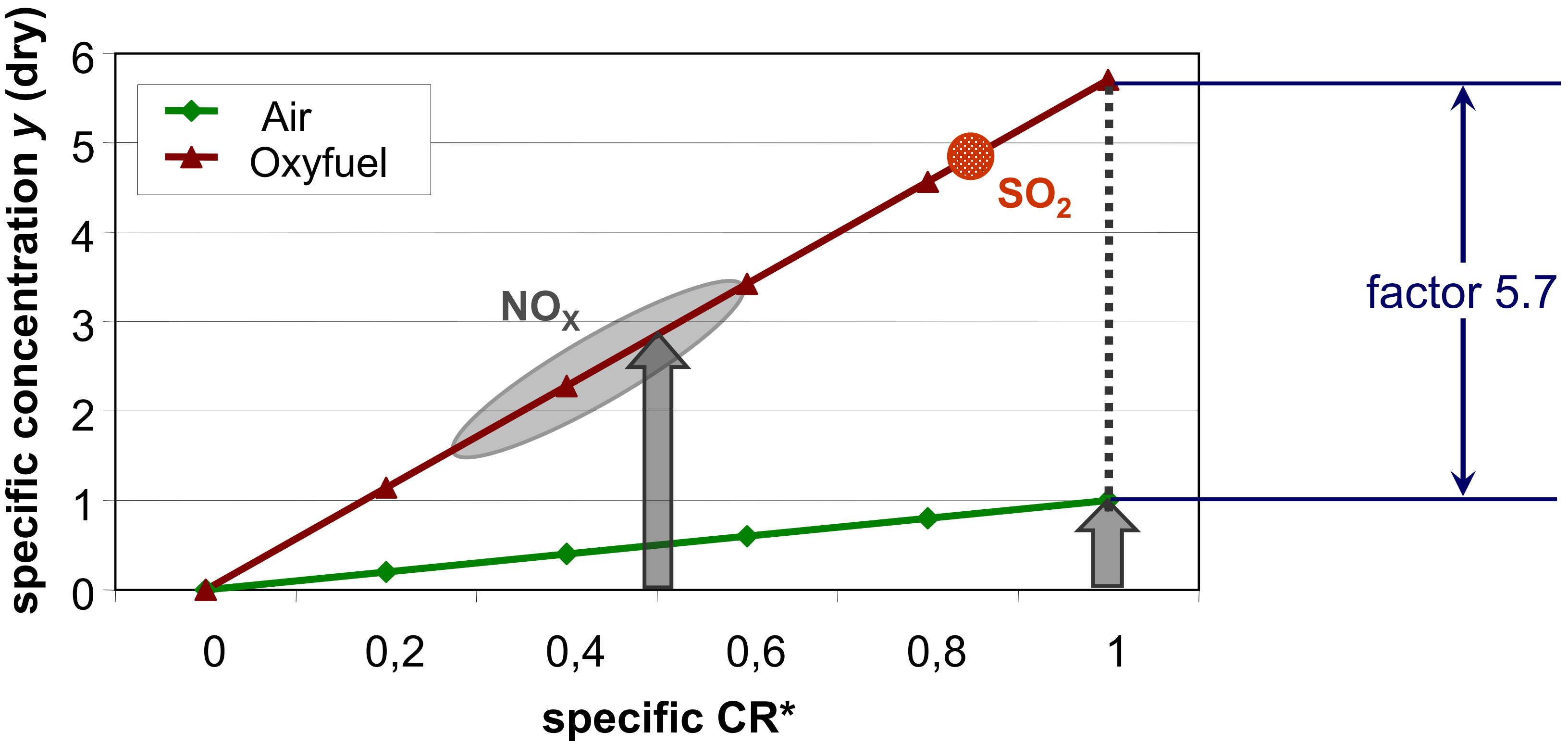
with particular regard to realistic design boundaries



$Q_{flue\ gas}$	MW	67.4
$m_{flue\ gas}$	kg/s	541
η_{boiler}	%	**94.5**

- **Significant increase of the boiler efficiency (approx. 4 %-pts) results in an overall efficiency increase potential of approx. 1.4 %-pts.**

⇨ **What is the potential under realistic boundary conditions?**



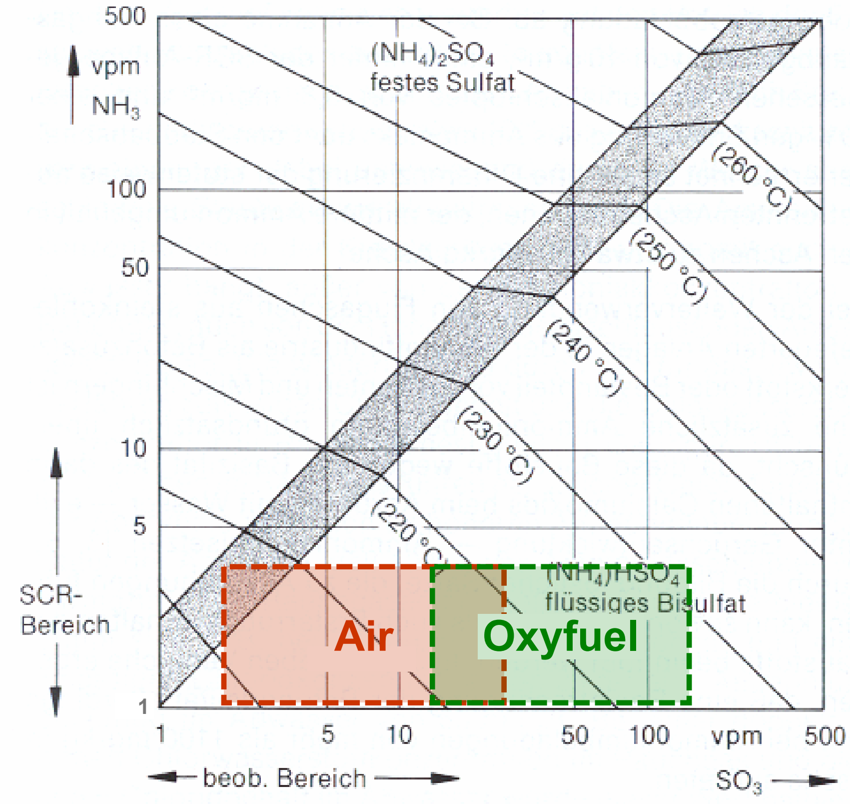
Causes:

- **lower specific flue gas mass flow**
- **increase of flue gas density**
- **higher water content in flue gas**
- **significant inhibition of NO_X formation**
- **SO_2 conversion rate (CR) similar to air case**

TUHH Technische Universität Hamburg-Harburg

NO_x

- **approx. 1200 mg/m³ @stp dry**
  - **Reduction prior to CO_2-condensation seems to be necessary**
- **High-dust SCR is a state-of-the-art technology**
  - **approx. 90 % NO_x conversion**
  - **NH_3 slip approx. 1.5 ppm_v**
  - **partial conversion of SO_2 ⇨ SO_3**
  - **formation of sticky and corrosive ammonium bisulfate, risk of scaling on downstream heat exchangers**



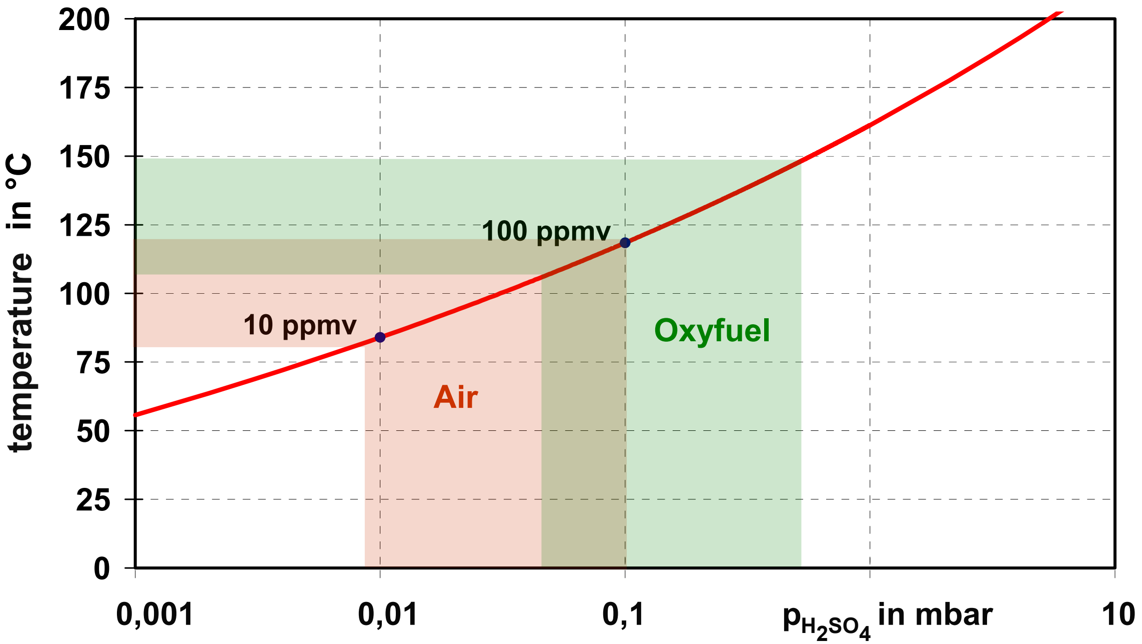
Formation temperatures of ammonium bisulfate and ammonium sulfate [Thyssen Engineering GmbH 1985]

SO_x

- SO_3 fraction of SO_x between 1 and 5 %
- SO_3 formation promoted by higher concentrations of oxygen and water
- higher concentration due to missing nitrogen

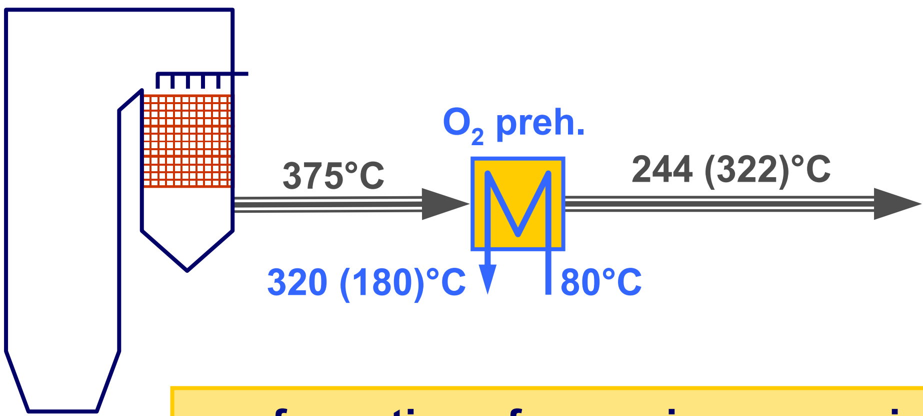
⇨ +20....40 K higher acid dew point temperature of the flue gas

vapour pressure curve of sulphuric acid



- Oxygen preheating (with a tubular heat exchanger)
  - \+ **maximum efficiency increase, identical in function as air preheating**
  - \- **high technical requirements of oxygen handling at elevated temperatures**
  - \- **low heat transfer coefficient (gas-gas) ⇨ large heating surface**
- Boiler feed water preheating
  - \+ **simple waste heat recovery process (similar to an economizer)**
  - \+ **low risks in case of damage**
  - \- **lower efficiency increase (compared with oxygen preheating) particularly for low pressure condensate preheating**
  - \- **complexity of controlling the bypass**
- Additional power cycle **(e.g. ORC)**
  - \+ **less complex design**
  - \+ **direct coupling with power turbines**
  - \- **lower efficiency increase compared with oxygen preheating**

Oxygen preheating

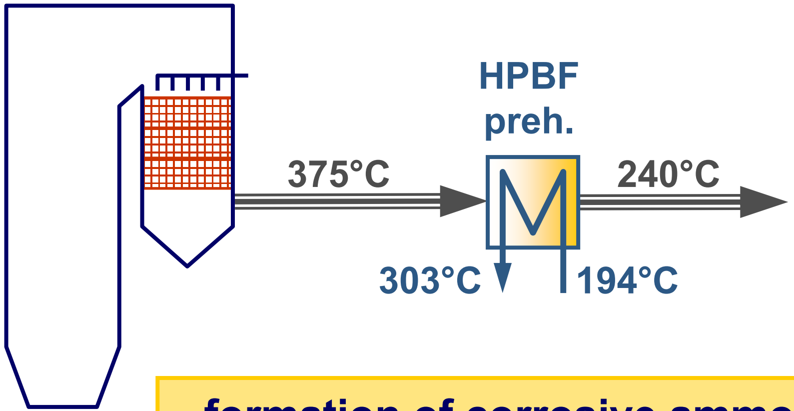


T_{oxygen}	°C	(180)	320
Q_{oxygen}	MW	9.1	21.9
$\Delta\ \eta_{net}$	%Pts	+0.6	+1.15

formation of corrosive ammonium bisulfate from NH_3 and SO_3

- **maximum efficiency increase**
- **Risk of damage as well as firmly bonded deposits at the oxygen preheater in the presence of an upstream high-dust SCR !**

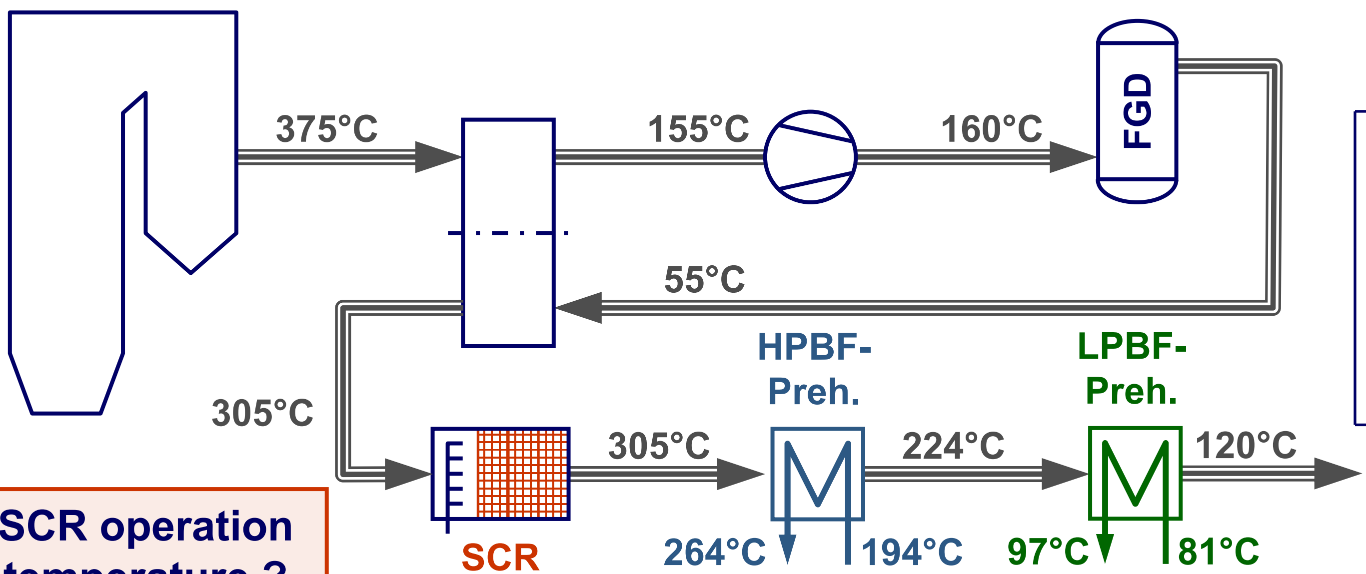
Boiler feed water preheating



Q_{HPBF}	MW	23.6
Q_{LPBF}	MW	-
$\Delta\eta_{net}$	%pts	1.05

formation of corrosive ammonium bisulfate from NH3 and SO3

low temperature corrosion



Q_{HPBF}	MW	12.7
Q_{LPBF}	MW	15.5
$\Delta\eta_{net}$	%pts	0.85

SCR operation temperature ?

- **Waste heat recovery from oxyfuel flue gas increases the overall net-efficiency significantly.**
- **Operation of a high dust SCR could cause problems with scaling and corrosion by ammonium bisulfate.**
- **Higher concentrations of SO_x increase the acid dew point temperature of the flue gas.**
  - higher risk of corrosion in case of low flue gas and water temperatures
- **Boiler feed water heating is the most promising option.**
  - high efficiency increase
  - limited risk of corrosion

Thank you

for your attention!

Oxy-fuel Coal-Fired Combustion Power Plant System Integration

Presented by:

Horst Hack
Foster Wheeler North America, USA

Minish Shah
Praxair Inc., USA

CO2 Reduction Strategy

Short and medium term approach

- Increase of efficiency provides emission cuts and has a direct impact on the use of natural resources, generation of waste matter and economics.
- Co-firing of solid fossil fuels with CO_2 neutral fuels in highly fuel-flexible CFB boilers in repowering and greenfield applications

GHG emission trading systems, emission caps and taxes are expected to lead into demand for solutions to near Zero Emission Power (ZEP) production of fossil fuels

- Retrofits - ZEP ready new plants - greenfield ZEP plants

Long-term approach - Technologies offering potential

- Post-combustion capture
- Pre-combustion capture (IGCC with CO_2 separation)
- Oxy-fuel combustion **⇐ Our main focus - (Oxy-CFB, Oxy-PC)**

Praxair – Foster Wheeler Alliance

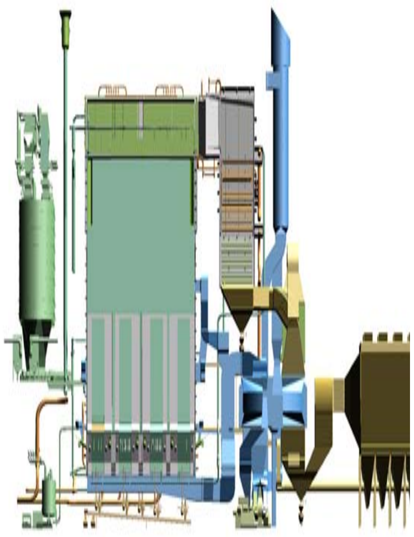
Alliance to pursue certain projects that will incorporate clean coal technologies and integrated oxy-coal combustion systems into coal-fired electric generating plants to facilitate capture and sequestration of carbon dioxide (CO2).

Validate scale-up of oxy-fuel technology

Improve integration of boiler with ASU and CCS systems

Oxy-Fuel Technology

Main Advantages



- The established PC/CFB advantages exist also in oxy-combustion.
- Multi-fuel capability in CFB (coal, petroleum coke, lignites etc.)
- Emission control technology, e.g. SO_x and NO_x reduction (performed better in oxy-mode)
- Dual-firing capability: Design PC/CFB boiler for both air-firing and oxy-fuel-firing.

Oxy-fuel is considered technically viable. Accurate design and performance prediction are challenging → Current/Future Work:

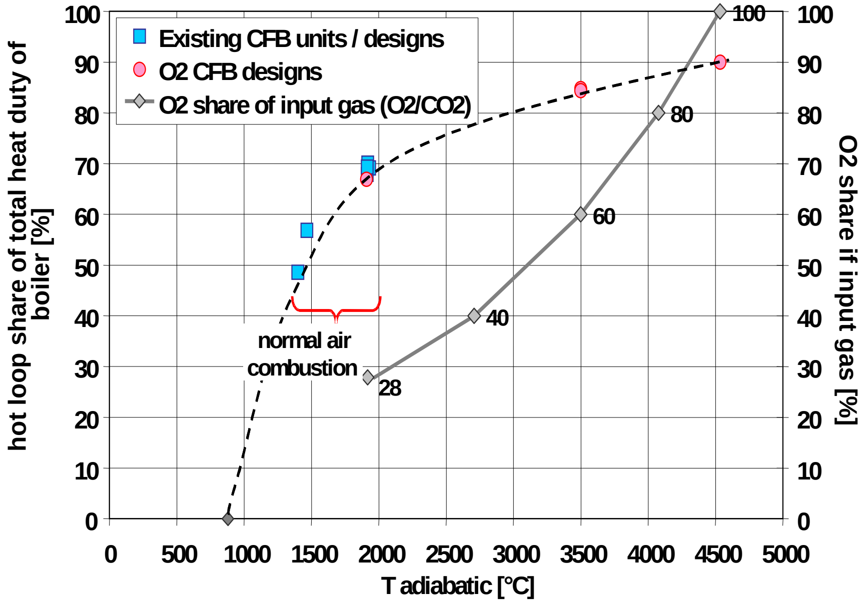
- Experiments in bench scale and pilot test facilities
- Development and validation of design models
- Long-term demonstration runs

Oxy-Fuel Technology

Challenges

Oxy-fuel gas property increase in:

- gas density
- gas mass flow rate at the same Ug
- gas moisture
- gas thermal capacity, Cp
- energy requirement for Fg*Cp*dT
- energy carryover to HRA
- heat transfer coefficient

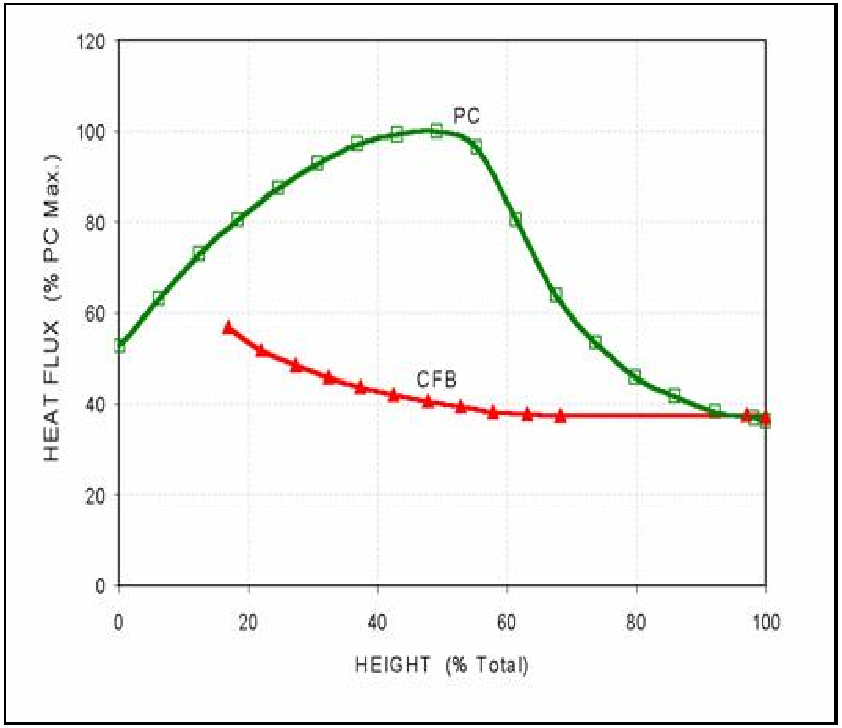


- Generated heat per volume is substantially higher than in combustion with air, as O2 concentrations increase
- Adiabatic combustion temperature rises
- Changes in hydrodynamics
- Materials in the high CO_2 and H_2O gas atmosphere
- Emissions prediction

Oxy-Fuel Technology

Furnace Heat Flux Control

- Balancing of temperature levels by fluegas recycling and firing rate
- Additional balancing of temperature levels by fluidized bed solid mixing in CFB
- FW CFB/INTREX and PC heat surface options available for higher energy absorption



Oxy-Fuel Retrofit Study

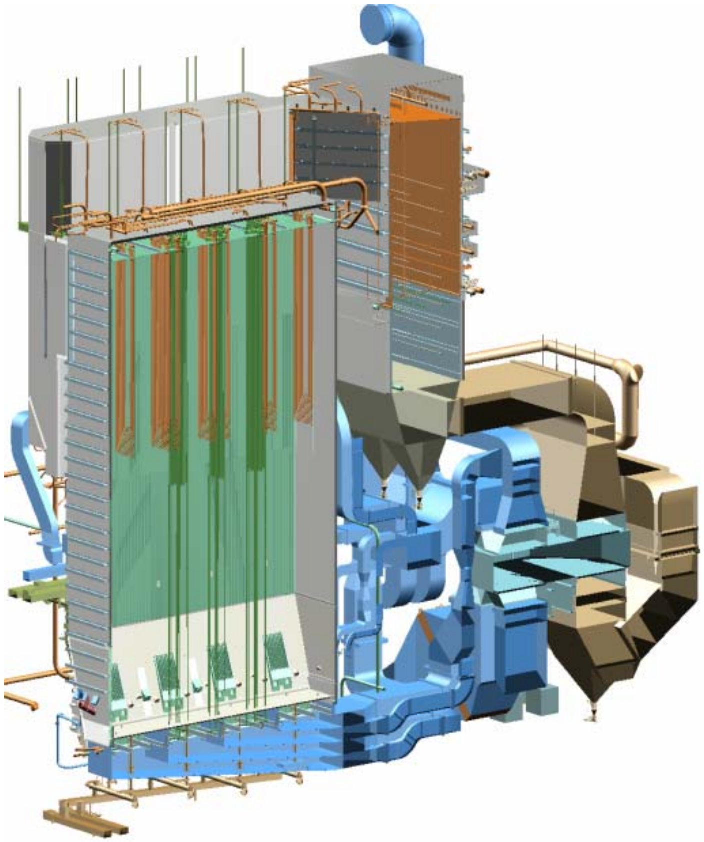
460 MWe Coal-Fired SC OTU CFB Boiler

Air-fired CFB reference plant:

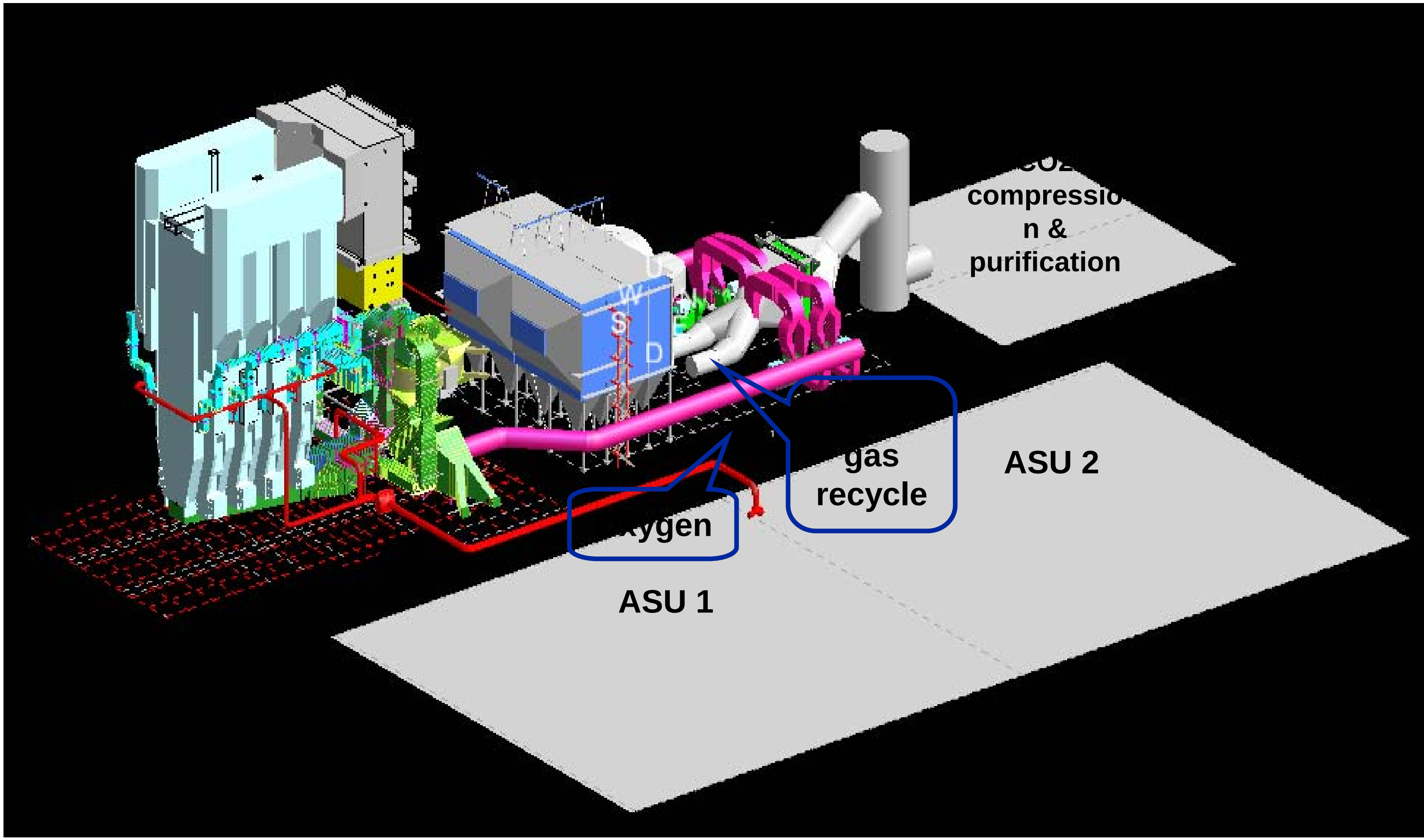
- Coal-fired FW SC OTU CFB boiler being constructed in Poland, 460 $MW_{e,\ gross}$, 439 $MW_{e,\ net}$, $\eta_{e,\ net}$ >43%

Conversion to oxy-fuel firing studied with different design tools

- Aspen Plus® for process system integration
- FW boiler performance design and calculation programs for mass and energy balances, size and heat surfaces etc



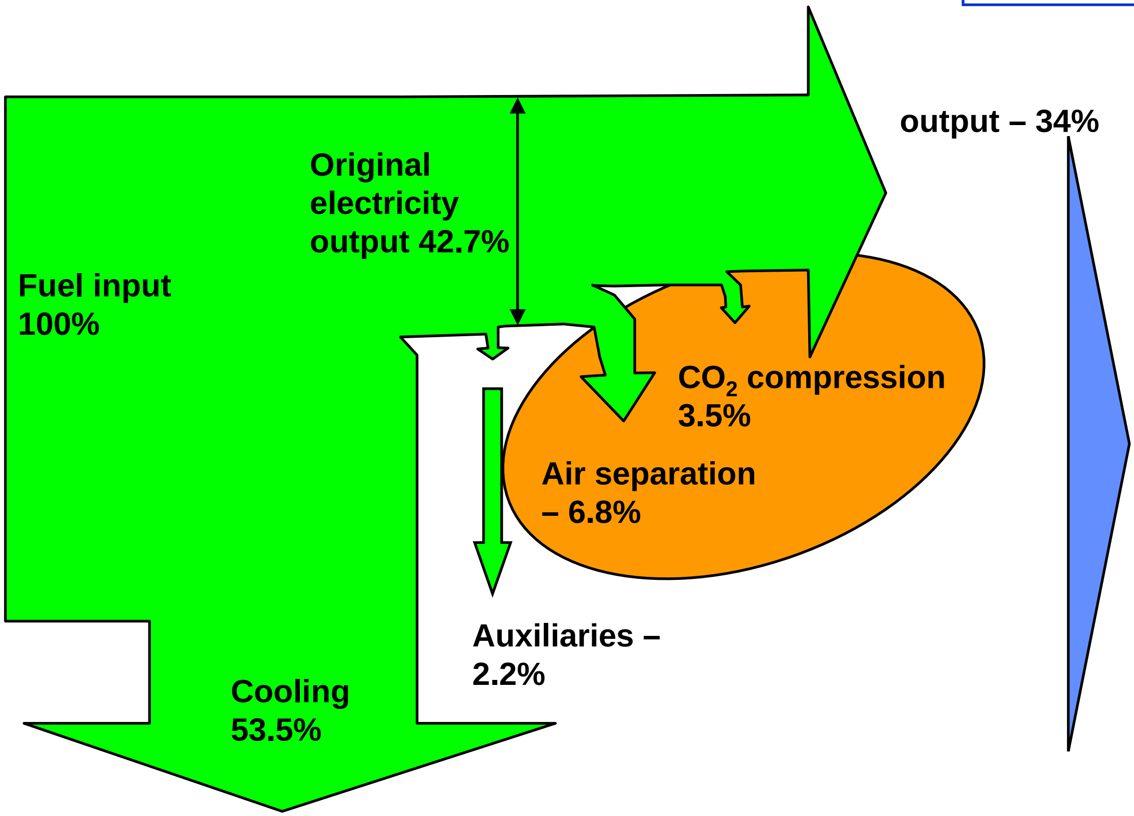
Oxy-CFB Boiler Retrofit Study Layout

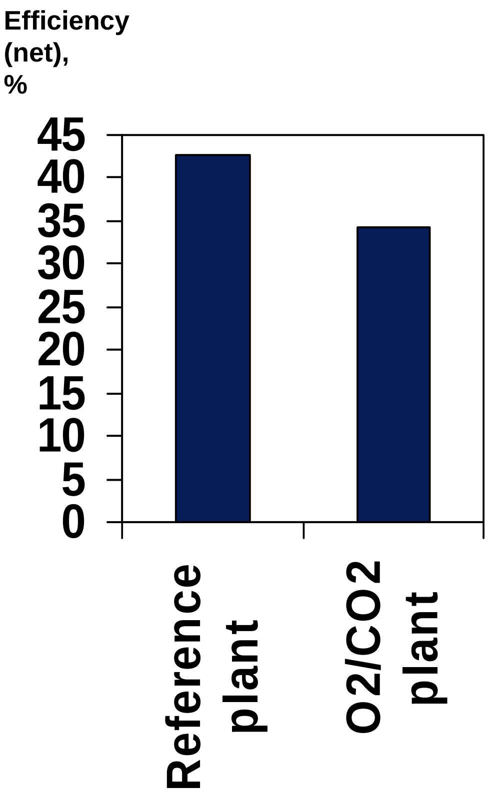


Penalty from Oxy-Fuel

Air separation and CO_2 compression require massive amounts of energy...

...resulting in 7-11 %-points lower efficiency, and 25% power derating → More new power plants req'd





Source: Chalmers / Andersson

Potential Solutions

in terms of $/tCO2, $/kW

Maximize component efficiency

- Advanced ST
- Advanced ASU configuration: 3-columns (wait for breakthrough technology)
- Advanced CPU configuration and with use of liquid CO2 pump if applicable

Maximize CO2 capture

- Enhance CO2 recovery by reducing inert gases
- Integration with vent gas recycling and purification

Increase power generation

- Fire-more to get more power (due to increased HTC and LMTD)
- Reduce aux power, and with use of more efficient steam driven compressors

Heat integration

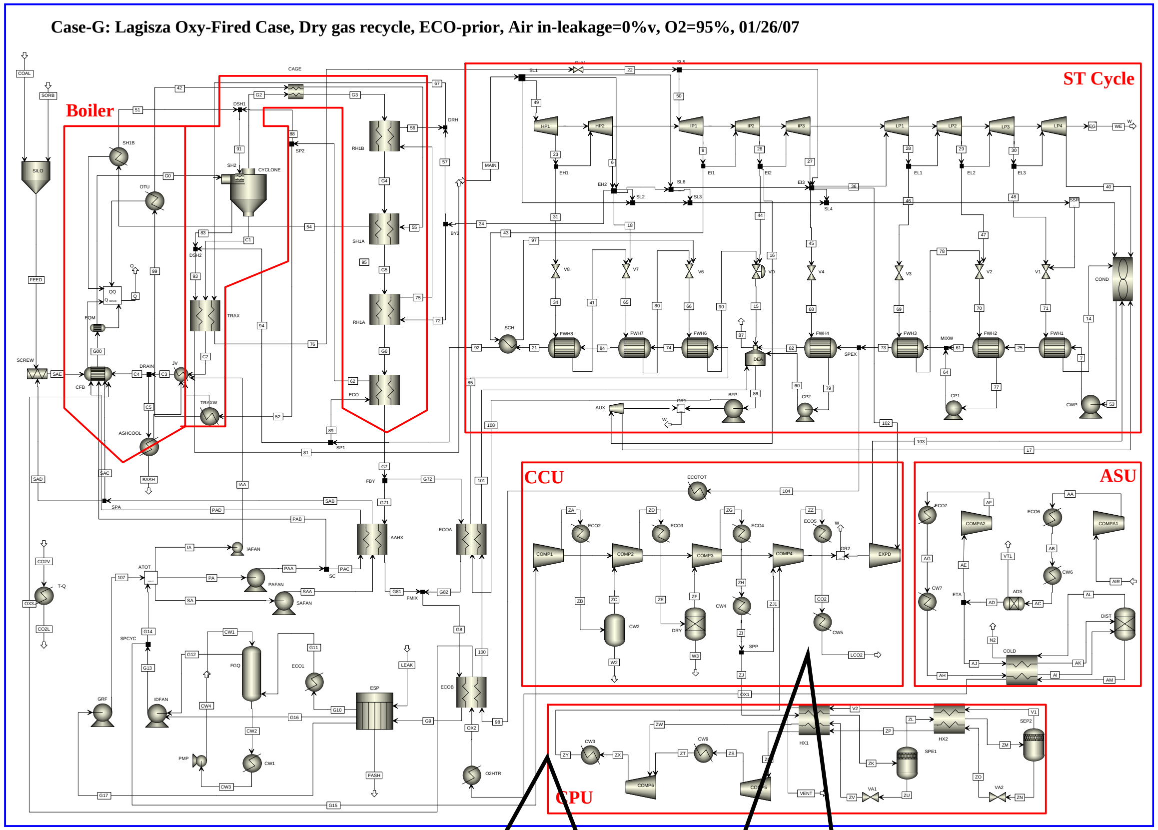
- Recover and integrate low-grade heat for power and efficiency
- Dual-firing boiler for better availability

Process Model

for challenges of integration and optimization

Parameters Studied:

- Dual-firing boiler
- Fire-more concept
- Hot/cold (w/d) recycle
- O_2 purity (95 or 99.4%v)
- Air ingress (0 or 3%)
- Heat recovery priority (gases or boiler water)
- CO_2 purification on/off
- Compressors driven by extracted steam



•CO_2 > 95%

•Outlet p > 110 bar

Dual (Air/Oxy)-Firing Boiler

Dual-firing for both peak power and CO_2 removal

– Air-Firing Mode: max power output for peak power in summer, daytime and weekdays

– Oxy-Firing Mode: low power demand in winter, weekends and overnight

– Potential for Oxy-ready boiler to be supplied before CO_2 capture required

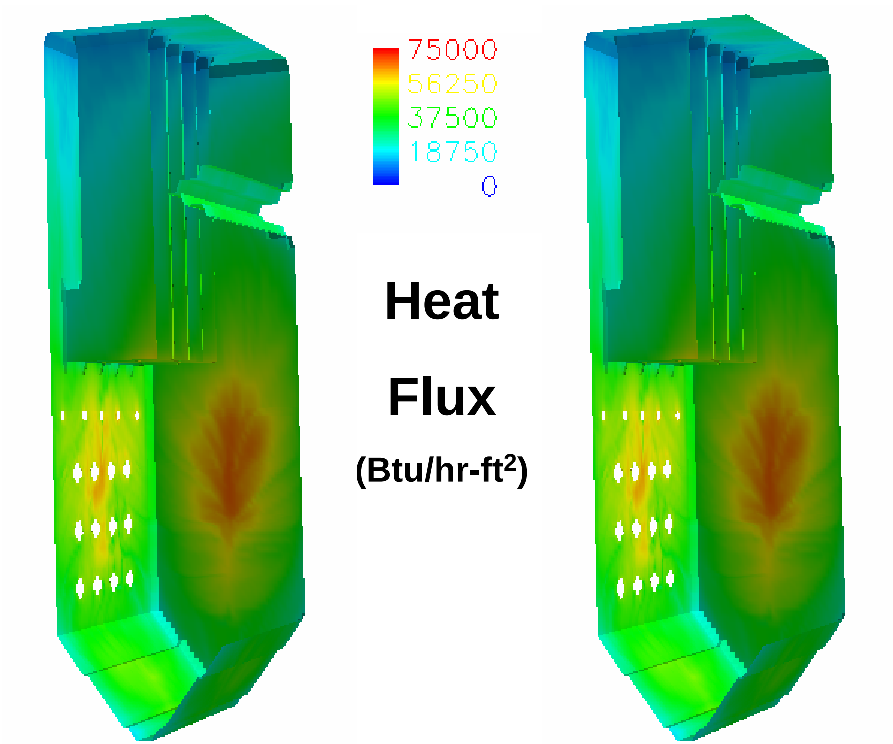
Dual-firing for better availability

– Power plant can fired in air-mode with 100% load in case of ASU, CPU, or pipeline trips

Dual-Firing PC 3D Modeling

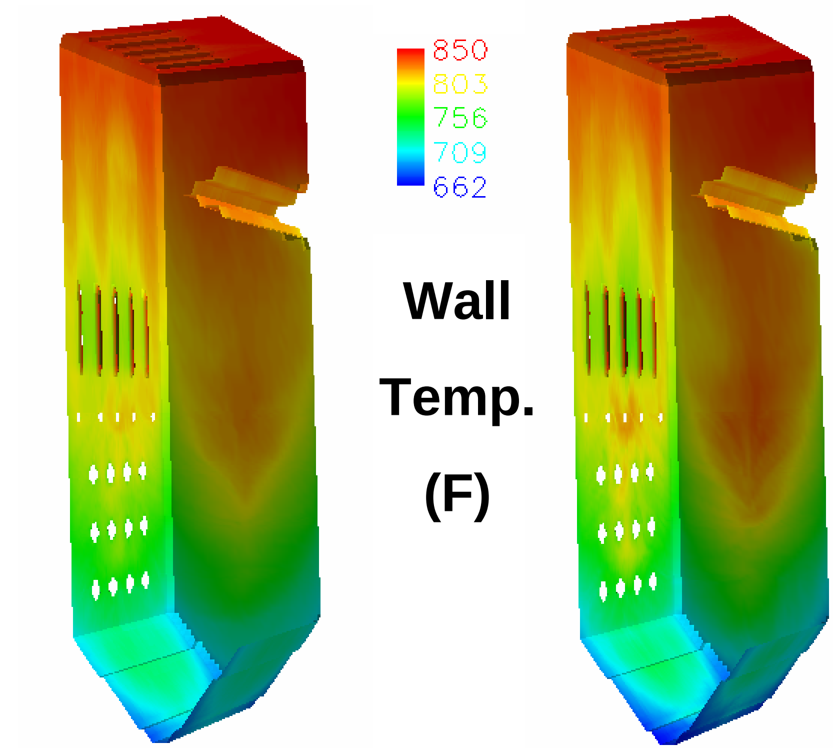
Optimized amount of gas recycling and firing rate

Air-Fired **O2-Fired**



Heat Flux
(Btu/hr-ft^2)

Air-Fired **O2-Fired**



Wall Temp. (F)

Firing-More Concept

At the same gas velocity and temperature, the furnace heat transfer coefficient increases in oxy-fuel mode due to flue gas physical properties

Firing-more to release more heat generates more steam using the same boiler, as a result of enhanced heat transfer coefficient, without increase of furnace temperature

Fire-more to maintain furnace gas velocity and heat flux

Extract extra steam from steam turbine to drive CO2 compressors to reduce auxiliary power load

Firing-More Benefits

Reduces auxiliary power, increase net power

- Net power reduction: 25% to 10%
- Specific power penalty reduction: 333 to 126 kWh/tCO_2

Allows operation in both air-mode and oxy-mode

Increases CO_2 removal

- CO_2 removal: 75 to 106 kg/s

Reduces cost per kW and COE

- Small increase in CAPEX and OPEX of ASU, CCU, Cooling, and solids handling
- Same boiler and auxiliaries

ASU Opportunities & Challenges

Reduce ASU power by 10%

Lower ASU capital by 20%

Heat integration

Optimum O_2 purity

Match power plant operation

ASU Power Reduction

Increase thermal integration in distillation system

- Reduces air compression requirements

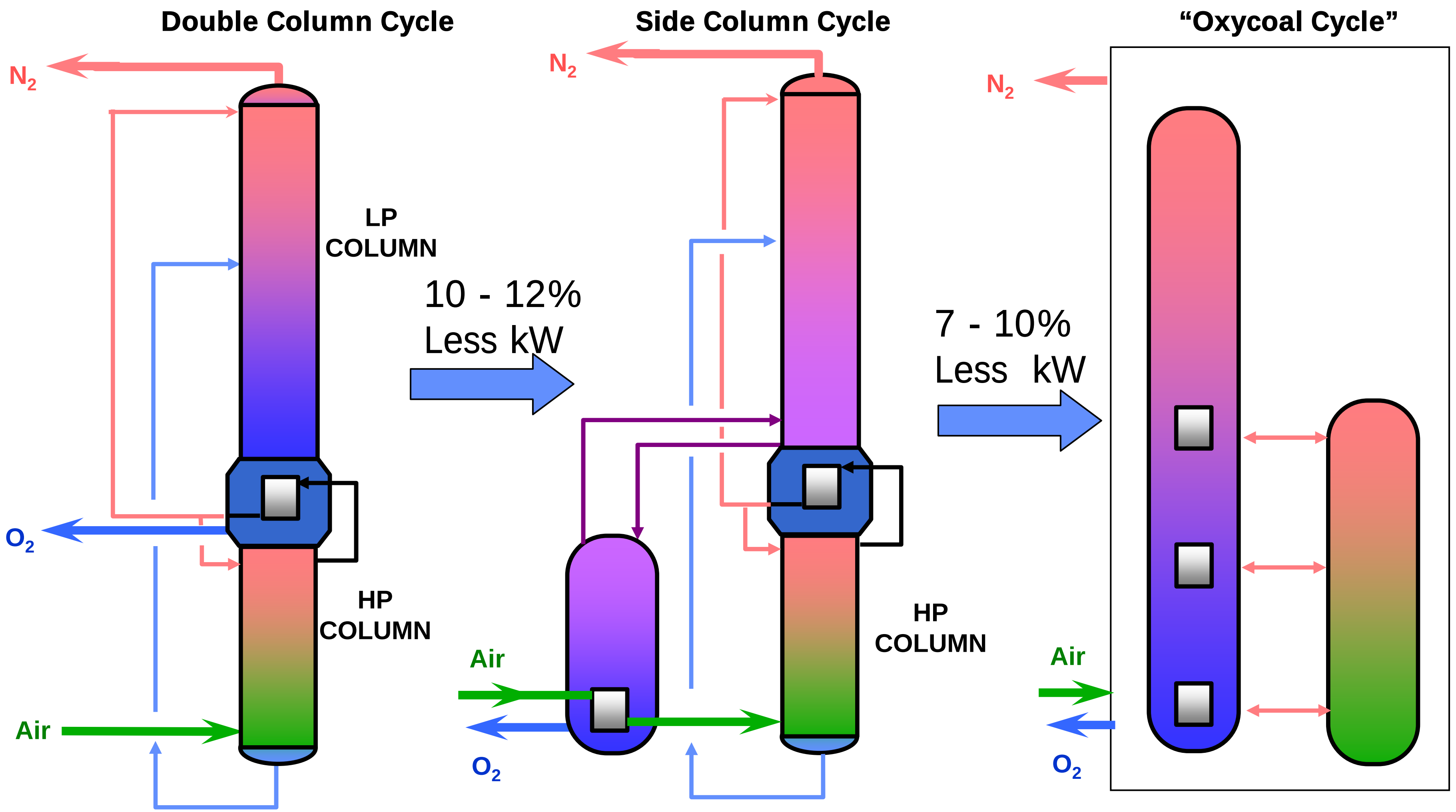
Reduce ΔPs

- Compressor intercoolers
- Prepurifier
- Distillation columns

Reduce ΔTs

- Primary heat exchanger for air cooling
- Cryogenic reboiler-condensers

Advancing Distillation Process



CO_2 Processing Unit (CPU) Opportunities & Challenges

Meet emissions & CO_2 purity regulations

Integration of compression and purification

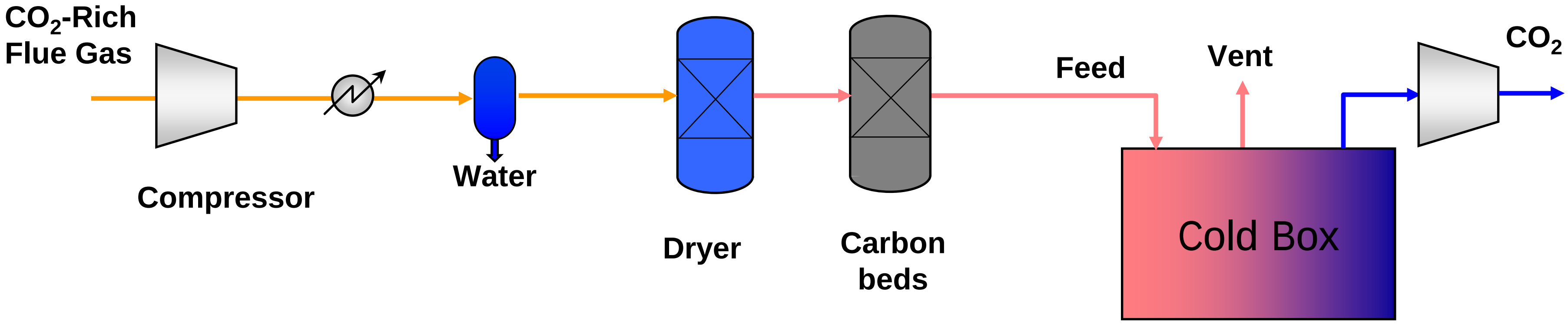
Impact of air ingress

Condensate treatment and disposal

CPU Schematics

Compression account for a majority of costs

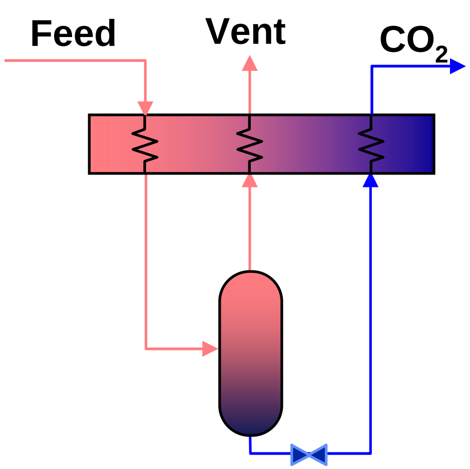
- CO_2 purity specification will dictate compression
- Cold box process optimization to minimize parasitic power



CO_2 Purification in Cold Box

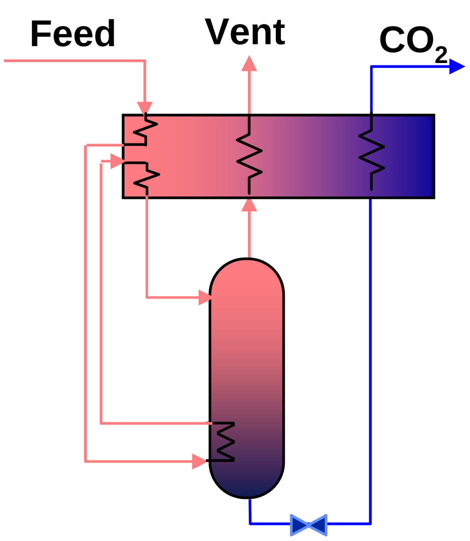
Min. 95% CO_2

One or two stage flash



99.9% CO_2

Distillation column needed



Conclusions

When major cuts of CO_2 emissions are required, CCS by oxy-fuel combustion appears technically feasible and cost competitive.

PC and CFB technologies provide flexibility for the design and operation under oxy-combustion conditions.

Experiments carried out so far have indicated good performance. More tests (emissions, heat transfer, materials, fouling...) are needed for further development and validation of design tools & solutions.

Technology demonstrations in fairly large scale and of extended periods are a necessary step when proceeding toward fully commercial size plants.

3rd IEAGHG International Oxy-Combustion Workshop
Yokohama, Japan, March 5-6, 2008

C E T C CANMET ENERGY TECHNOLOGY CENTRE

3rd Generation Oxy-Fuel Combustion Systems

CLEAN ENERGY TECHNOLOGIES

Kourosh E. Zanganeh, Carlos Salvador, Milenka Mitrovic, and Ahmed Shafeen

Zero-Emission Technologies Group

CANMET Energy Technology Centre – Ottawa

Natural Resources Canada — Ressources naturelles Canada

Canada

CO_2 Strategy Options for Power Sector

Efficiency Increase

1. Parameter
higher temperature & new materials
(e.g. nickel alloys, ceramics)

2. Technology
improved machinery
(e.g. turbine blades)

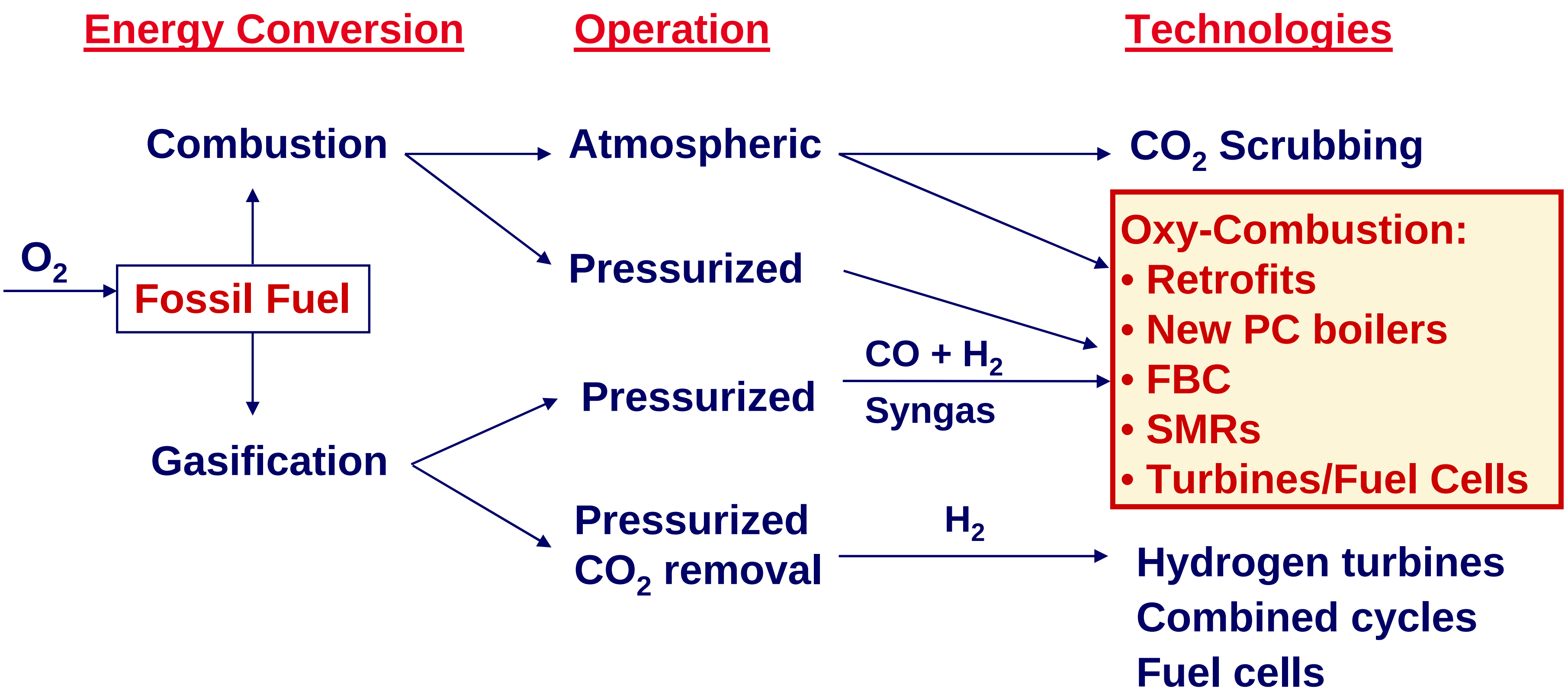
3. Process
new combined cycles
(e.g. IGCC, PFBC, PPCC, EFCC)

CO_2 Capture and Storage

1. Process
- pre-combustion capture
- post-combustion capture
- oxy-fuel combustion

2. Storage of CO_2
- aquifer
- oil-fields
- gas-fields
- coal-fields

Oxy-Fuel Combustion Technology Pathways



Oxy-fuel Technology Generic Opportunities

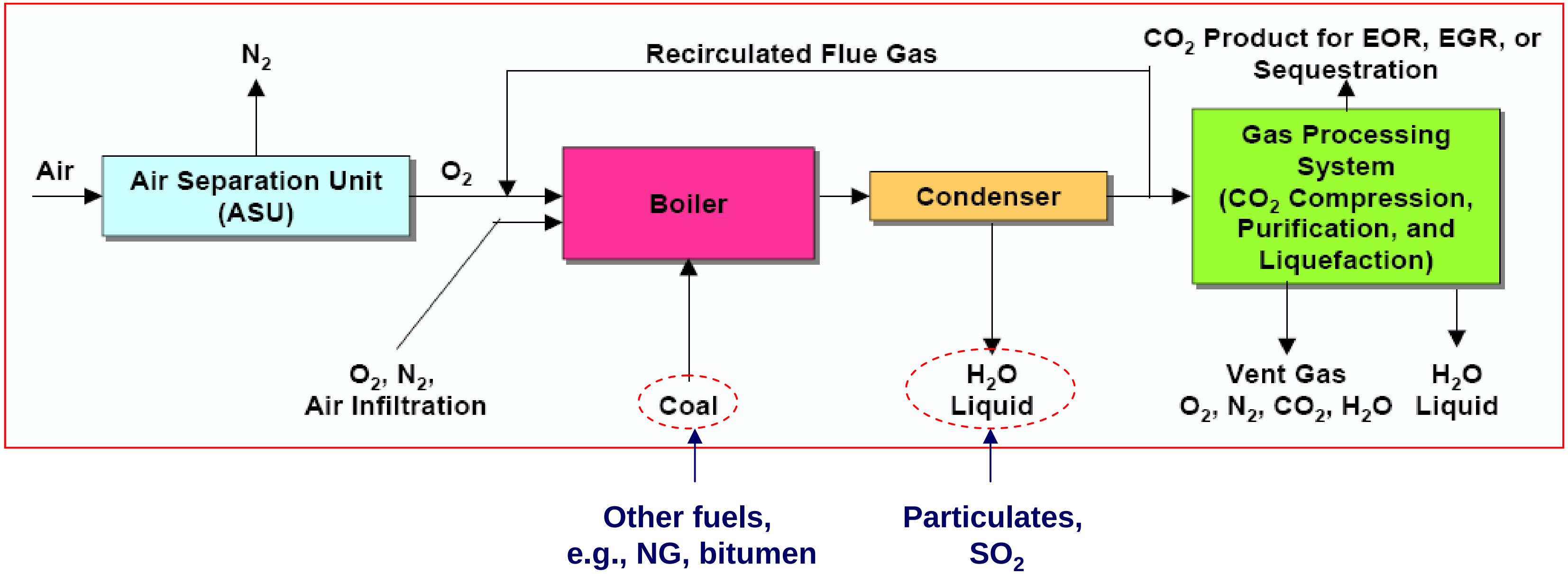
- Produces a highly concentrated stream of CO_2, ready for capture and storage
- Offers excellent opportunities for integrated emissions control through reduced flue gas flow
- Can Eliminate the need for downstream NO_x Control
- With pure O_2 combustion, the unit size/volume may be reduced to $1/5^{th}$ of air-fired combustion

Oxy-fuel Technology Generic Needs

- Increased knowledge on fundamentals of combustion behavior and emissions formation/reduction
- Development of new component design and layout (boiler, burner, fuel feeding system, flue gas cleaning and recirculation devices...)
- Optimization of flue gas treatment and CO_2 processing to balance:
  - Environmental issues
  - Investment cost
  - Operational issues
- CO_2 product requirements (including effect on transport and storage system and risk and environmental aspects)
- CO_2 recovery and energy cost reduction
- O_2 production and energy cost reduction for air separation unit

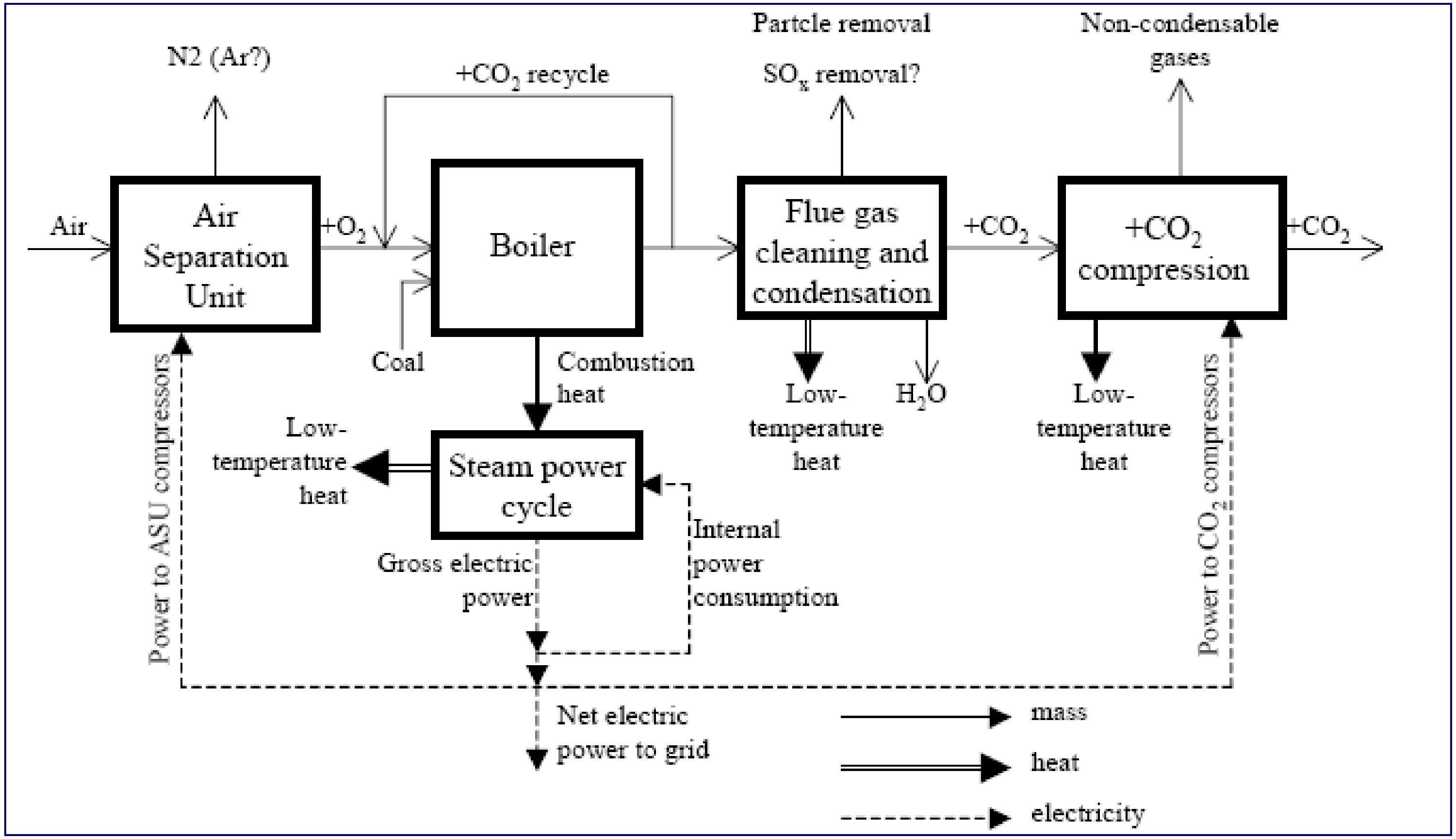
1st Generation Oxy-fuel Combustion Systems

- No reduction in unit size/volume compared to air-fired combustion (up to flue gas recycle point)
- No efficient integration and optimization of the process
- No recovery of low temperature heat
- Need to design the whole plant as a gas-tight system and for flue gas recycle to transport coal from the mills
  - CO_2 and hot gas leakage out versus air leakage in
  - Need for gas-tight mills and pre-treatment of the primary recycle flow



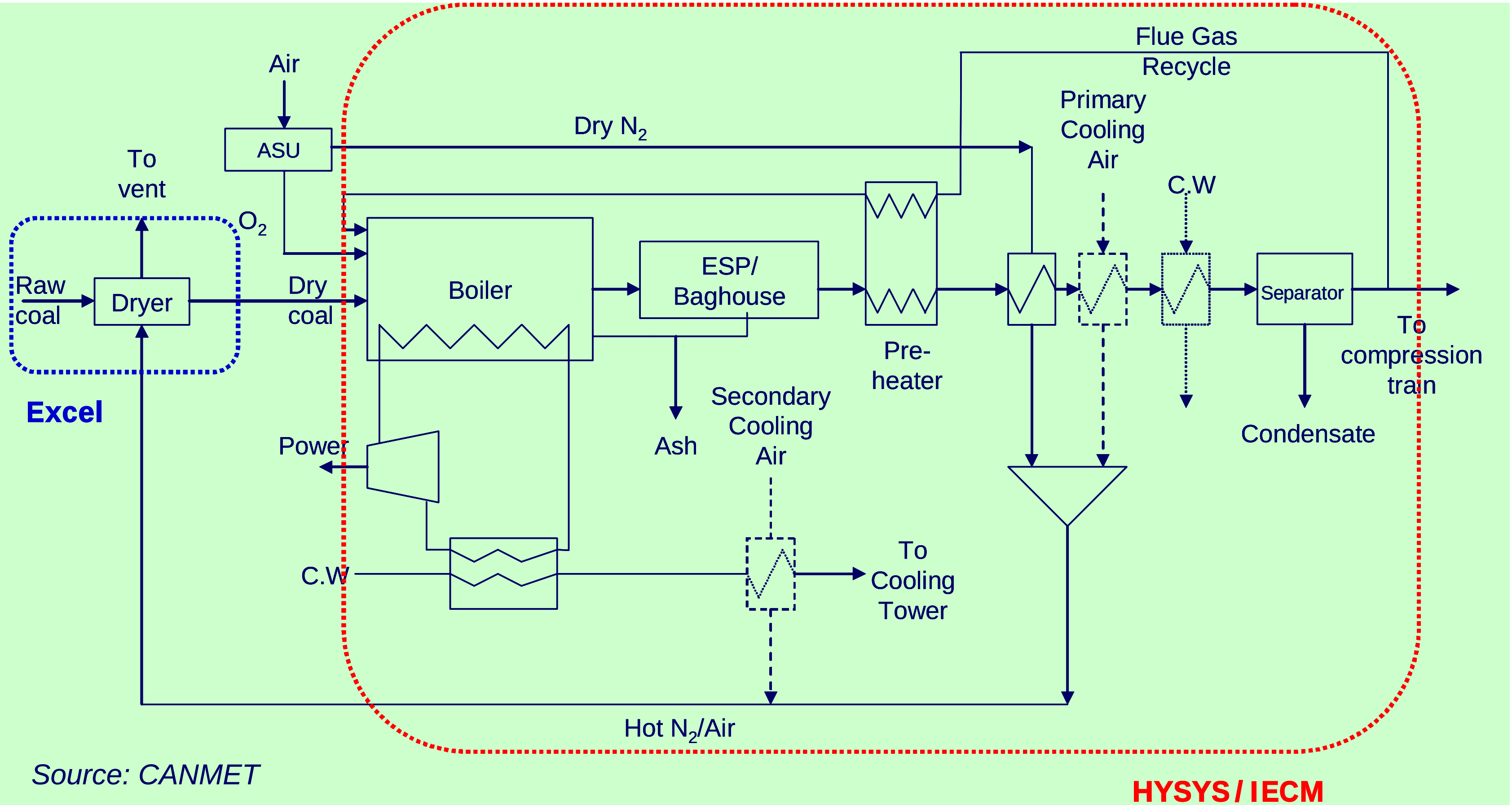
2nd Generation Oxy-Combustion Systems

- Energy efficient integration and optimization of the process, recovery of low temperature heat



2nd Generation Oxy-Combustion Systems (*cont…*)

- **Integrated oxy-coal combustion with coal drying concept**

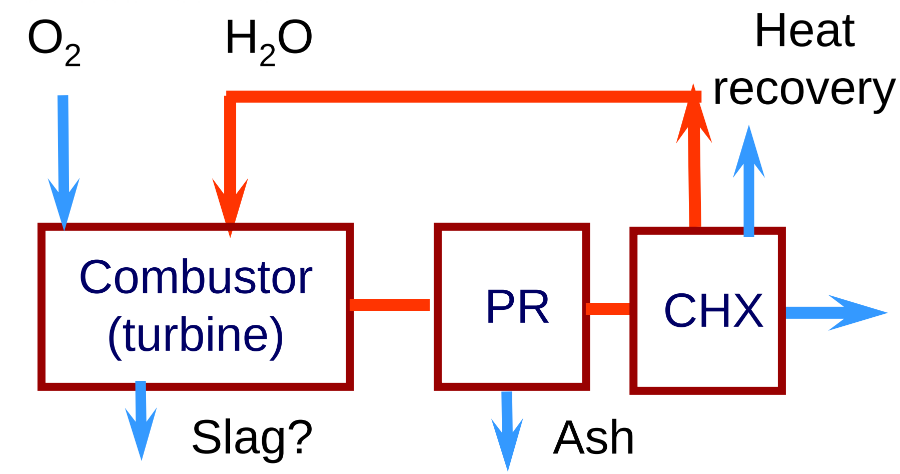


Source: CANMET

Need for New Concepts and Technologies

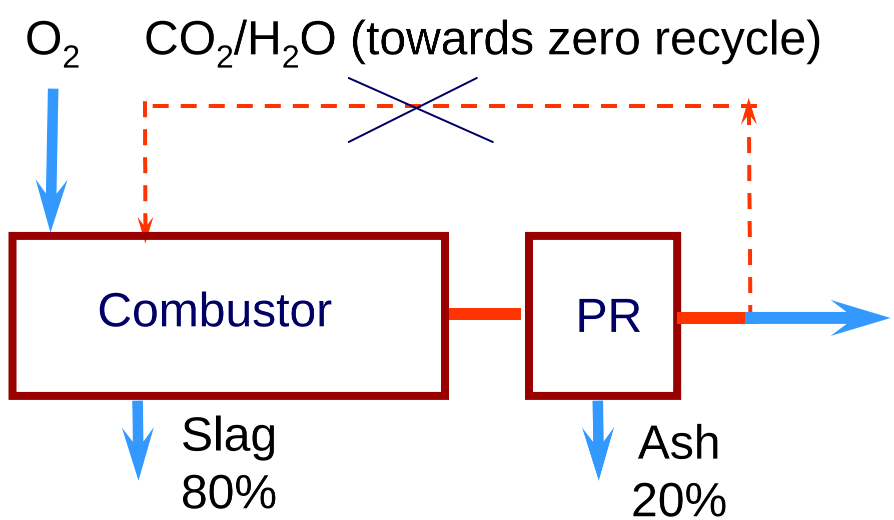
- Design for plant life
  - **Current and future needs (CO_2 market, etc.)**
  - **Flexibility in design to adapt**
  - **Environmental regulations (near zero emissions for fossil fuels)**
  - **Low-value fuels and co-firing (bitumen, petcoke, biomass, etc)**
- Advancements in technology, e.g.,
  - **Ion transport membrane for O_2 production**
  - **CO_2 membrane for separation**
  - **High temperature materials (boiler tubes, etc)**
- Moving away from Rankin cycle (lower efficiency)
  - **3rd generation of oxy-fuel combustion systems**
  - **Advanced turbines and power cycles**
  - **Pressurized with direct CO_2 capture**

3rd Generation Oxy-Fuel Systems



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

Up to 40% scale reduction in unit size



- ***Minimize NO_x & excess O_2,***
- ***High radiative & convective heat transfer,***
- ***New materials for combustor***
- ***process model, CFD, system and component design***

Up to 80% scale reduction in unit size

CANMET Program Background

Zero Emission Oxy-Fuel Combustion Technologies for Clean Fossil Fuels:

- The program started at CANMET in Mid 2004 and has already led to several new concepts and novel prototype designs
- The primary focus of the program is the development of the new generation of near-zero emission oxy-fuel combustion technologies with higher efficiency and significantly lower capital and operating costs.
- The scope covers three distinct, novel and advanced R&D technology areas:
  - Hydroxy-fuel (or oxy-steam) combustion technology;
  - Pure oxygen slagging combustion technology; and,
  - CO_2 capture and compression technology.

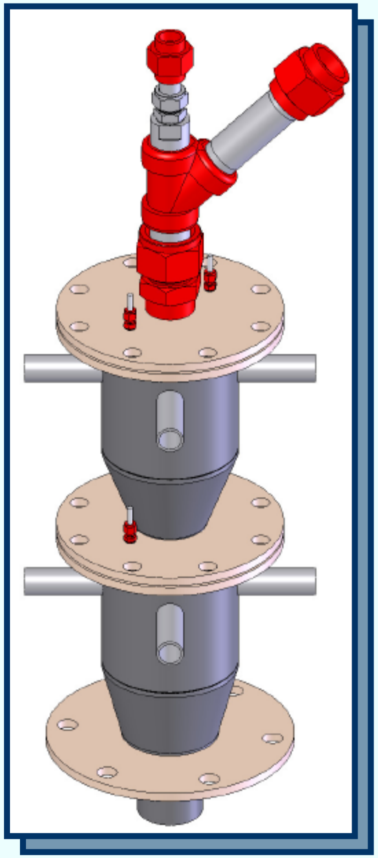
Hydroxy-Fuel Technology Development

Overall Objectives:

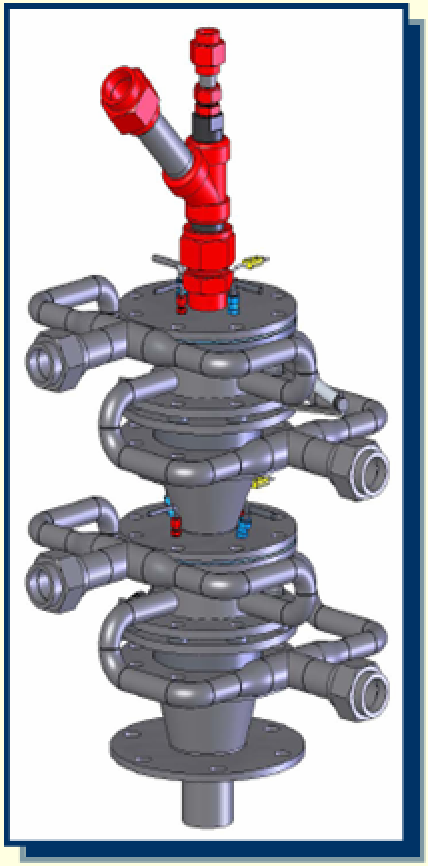
- Investigate the feasibility of hydroxy-fuel combustion for the 3rd generation oxy-fuel systems
- Realize the reduction in size and capital cost of equipment
- Use water or steam, preferably with no FGR, to moderate the flame temperature
- Achieve high concentration of CO_2 (on dry basis) in the exit flue gas stream

Hydroxy-Fuel Burner Prototypes

1st Generation: Fixed-Angle Swirl Generator



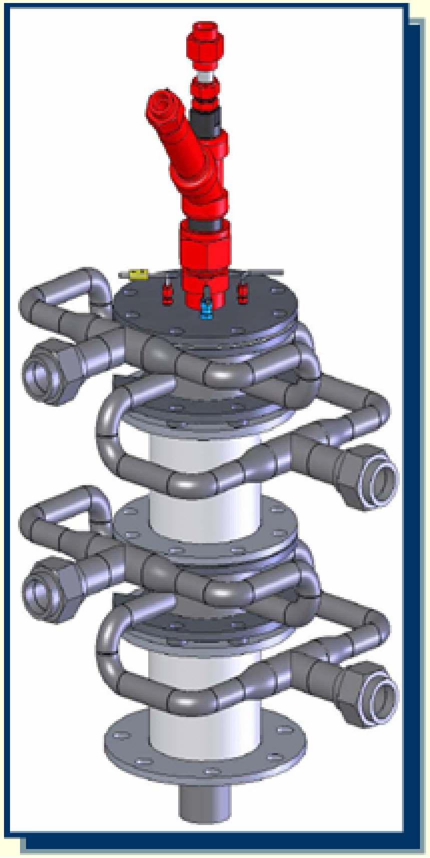
2nd Generation: Variable-Angle Swirl Generator



Hydroxy-Fuel Burner Prototypes *(cont.)*

- Design Features:
  - Fuels:
    - Natural gas
    - Oil, Emulsion
    - Pulverized coal and coal slurry
  - Operational modes
    - ***O_2/steam***
    - O_2/RFG & O_2/CO_2
    - Air & oxygen enriched air
    - ***O_2/steam/RFG***
    - ***O_2/steam/CO_2***
  - Variable secondary & tertiary stream mass flow rates
  - Variable secondary & tertiary steam oxygen concentration
  - Independent secondary & tertiary stream swirl

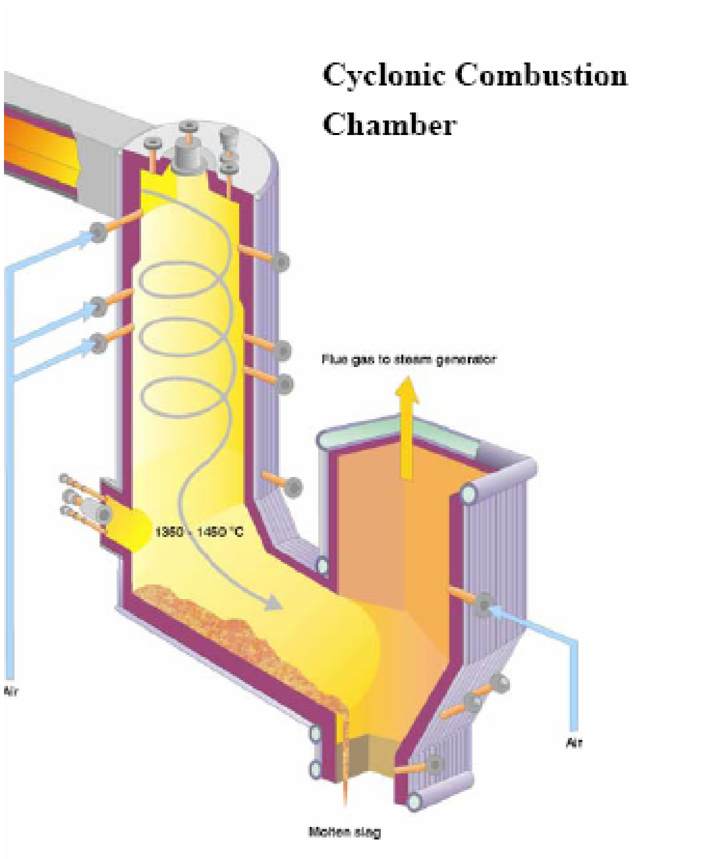
4th Generation:
Variable Swirl Block Generator



Pure O_2 Slagging Combustor Technology Development

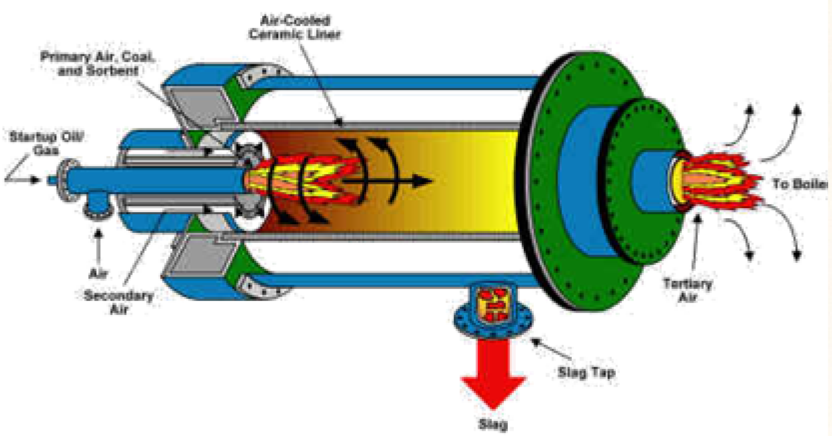
Overall Objectives:

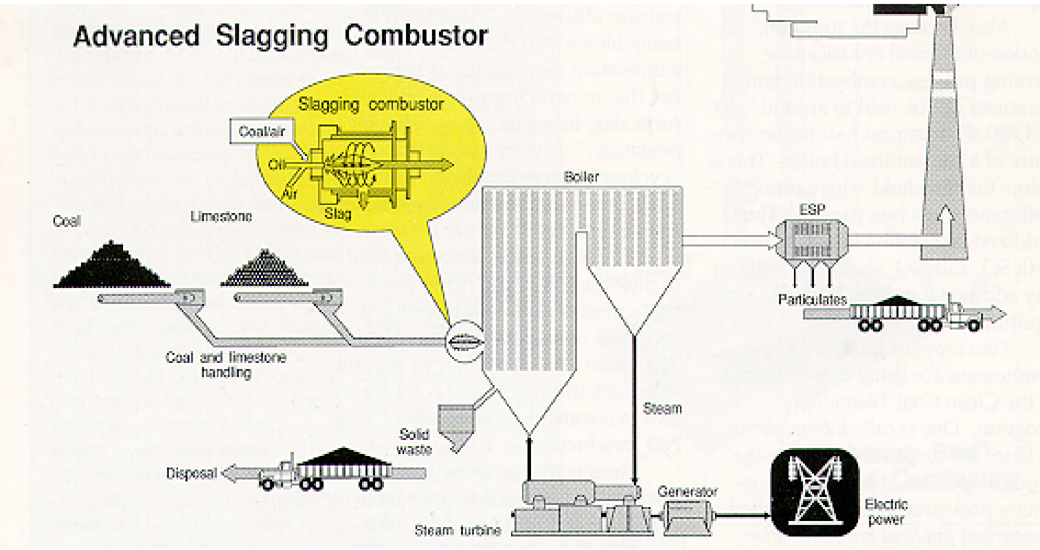
- Investigate the feasibility of pure oxy-coal combustion in slagging mode for the 3rd generation oxy-fuel systems
- Realize the reduction in size and capital cost of equipment
- Demonstrate the technology at pilot-scale
- Investigate the scale up options



Background Technology

- Slagging combustor - Features
  - Burn coal (e.g., high-ash) or co-firing with other opportunity fuels
  - Typical design includes
    - Fuel and primary stream are introduced either axially or tangentially
    - Secondary stream is introduced tangentially
    - Centrifugal forces propel the ash to the wall to form slag
    - Molten slag is drained by gravity
    - 75-85% of ash is removed



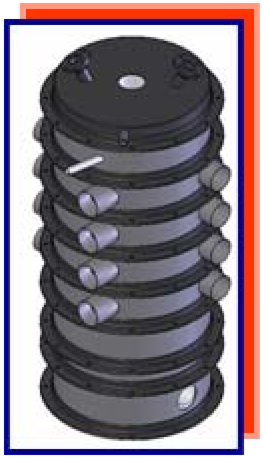
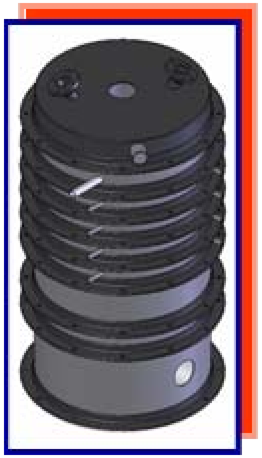
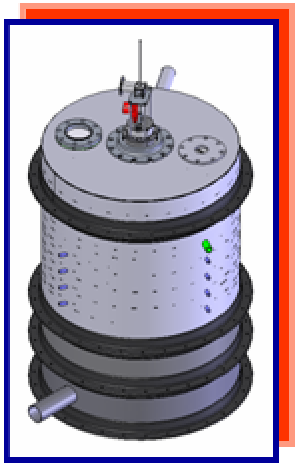


Design Challenges

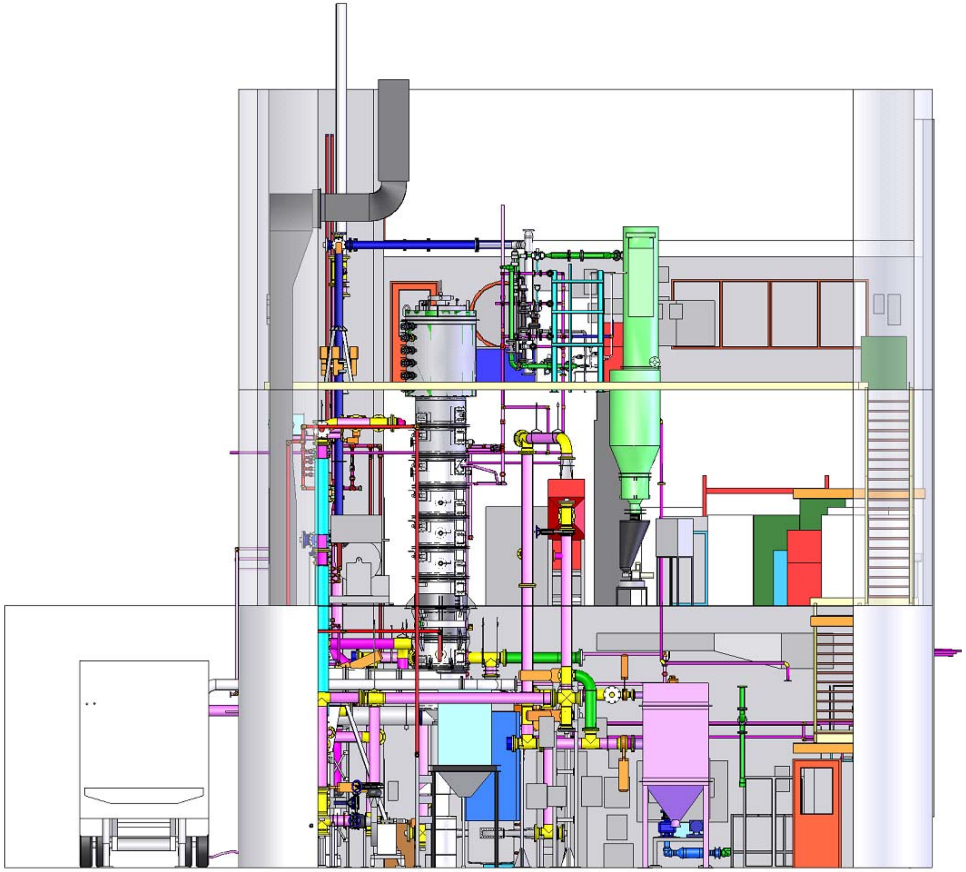
- Highly innovative and compact design
- High-temperature and corrosive environment
- Cooling system design and integration
- Slag removal
- Model slag formation, flow, and impact on performance
- Integration issues
- Process control and monitoring

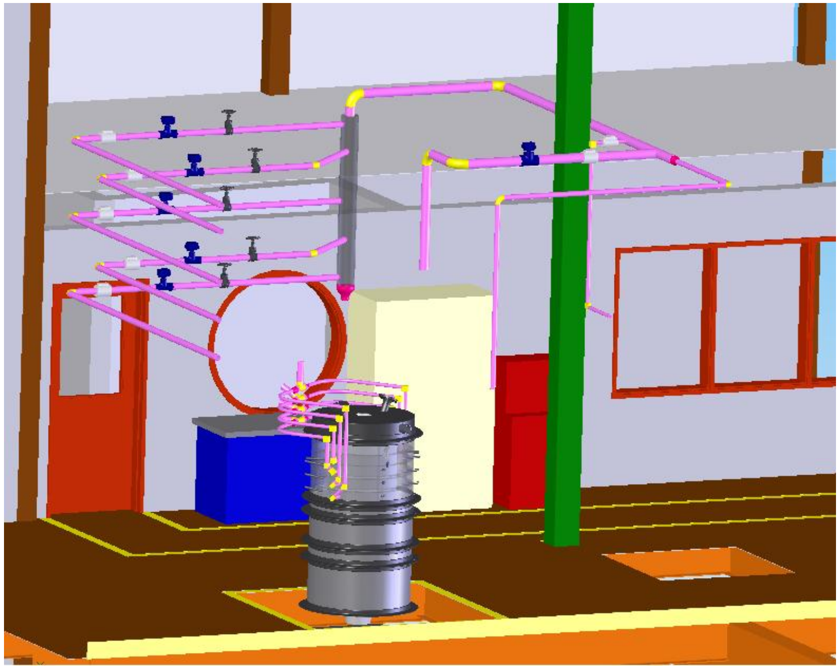
Prototype Design

- Five prototype designs have been completed
- Operating modes:
  - Pure O_2 combustion
  - Enriched air combustion
  - O_2/CO_2
  - O_2/RFG

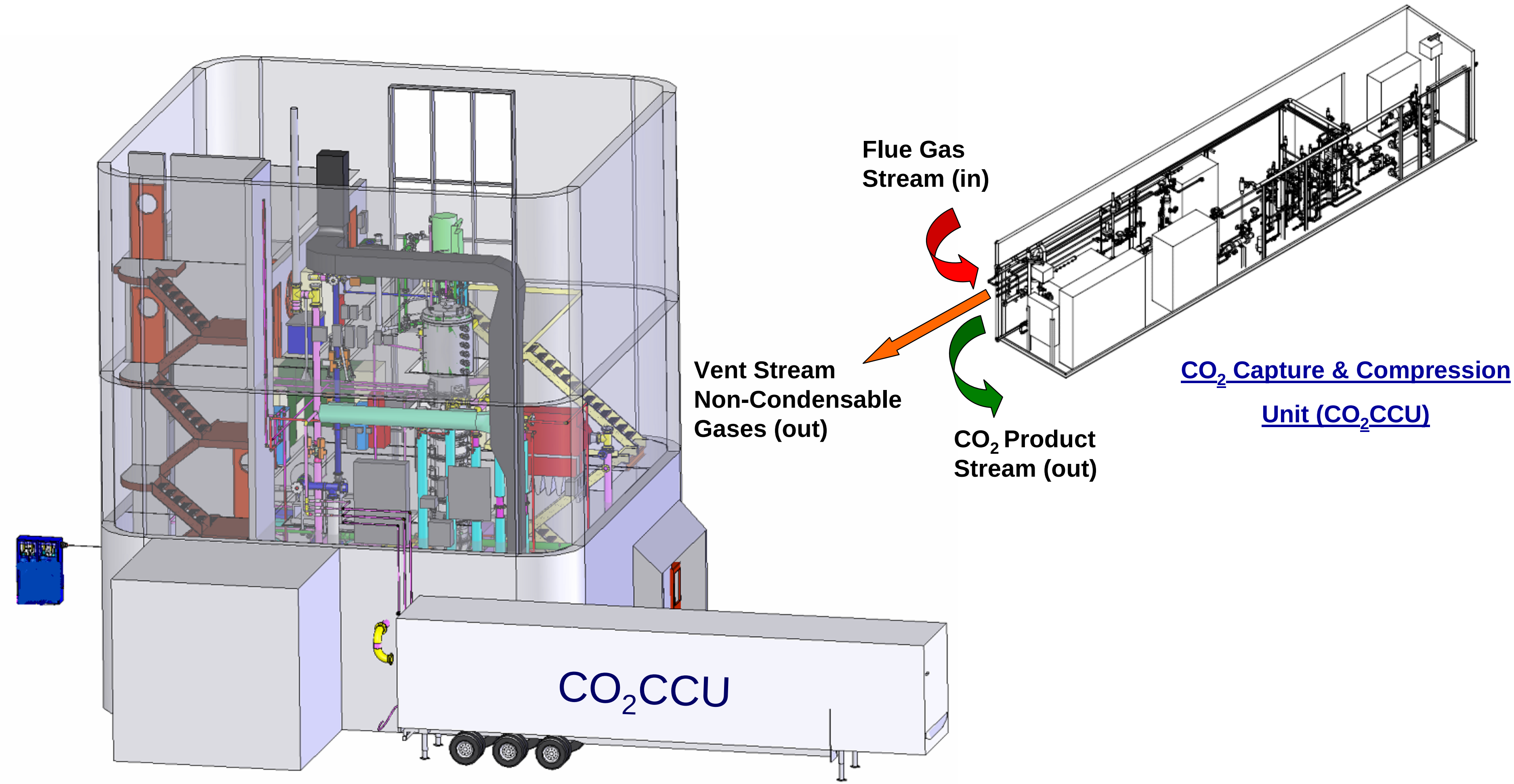
Prototype 1	Prototype 2	Prototype 3	Prototype 4	Prototype 5
				

Integration with Vertical Combustor Research Facility (VCRF)





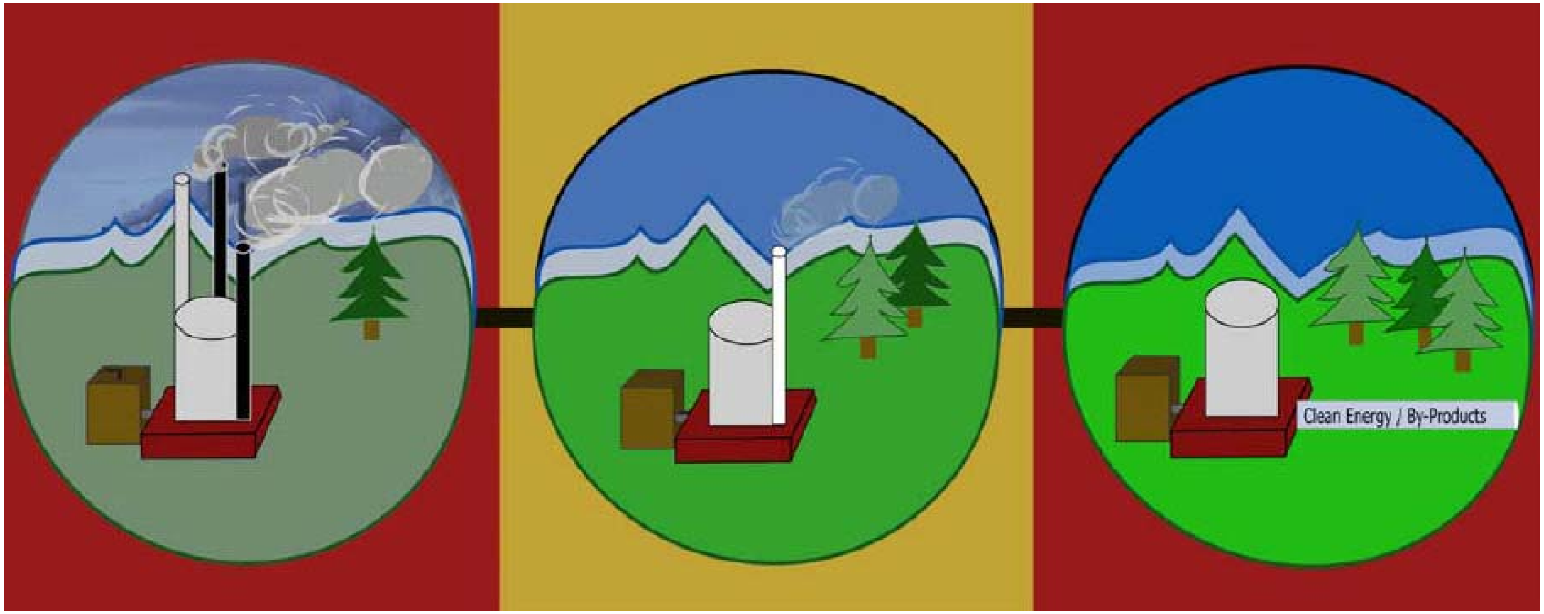
Integrated CO_2 Capture and Compression Unit



Acknowledgement

Much of the knowledge gained in oxy-fuel combustion technology enabling this presentation came from pioneering research and development undertaken in this area for more than a decade at CANMET Energy Technology Centre in Ottawa.

Funding for this program provided by the Program of Energy Research and Development (PERD), a federal, interdepartmental program operated by Natural Resources Canada, and the CANMET CO_2 R&D Consortium.



Thank You

O_2/RFG Combustion

OXY-COMBUSTION: RESEARCH, DEVELOPMENT AND SYSTEMS ANALYSIS

Timothy Fout

3rd Workshop of the IEAGHG International Oxy-Combustion Network

Yokohama, Japan

March 5, 2008

National Energy Technology Laboratory

Outline for Presentation

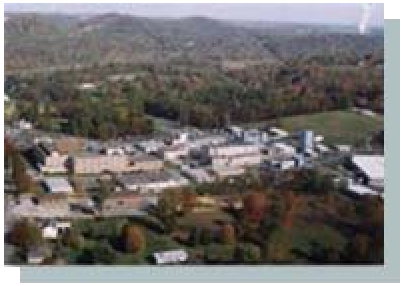
- NETL Overview
- Background
- Carbon Sequestration Program
- Oxy-combustion Research
- Systems Analysis

National Energy Technology Laboratory

- **Only DOE national lab dedicated to fossil energy**
  - Fossil fuels provide 85% of U.S. energy supply
- **One lab, five locations, one management structure**
- **1,100 Federal and support-contractor employees**
- **Research spans fundamental science to technology demonstrations**

Pennsylvania

Oregon



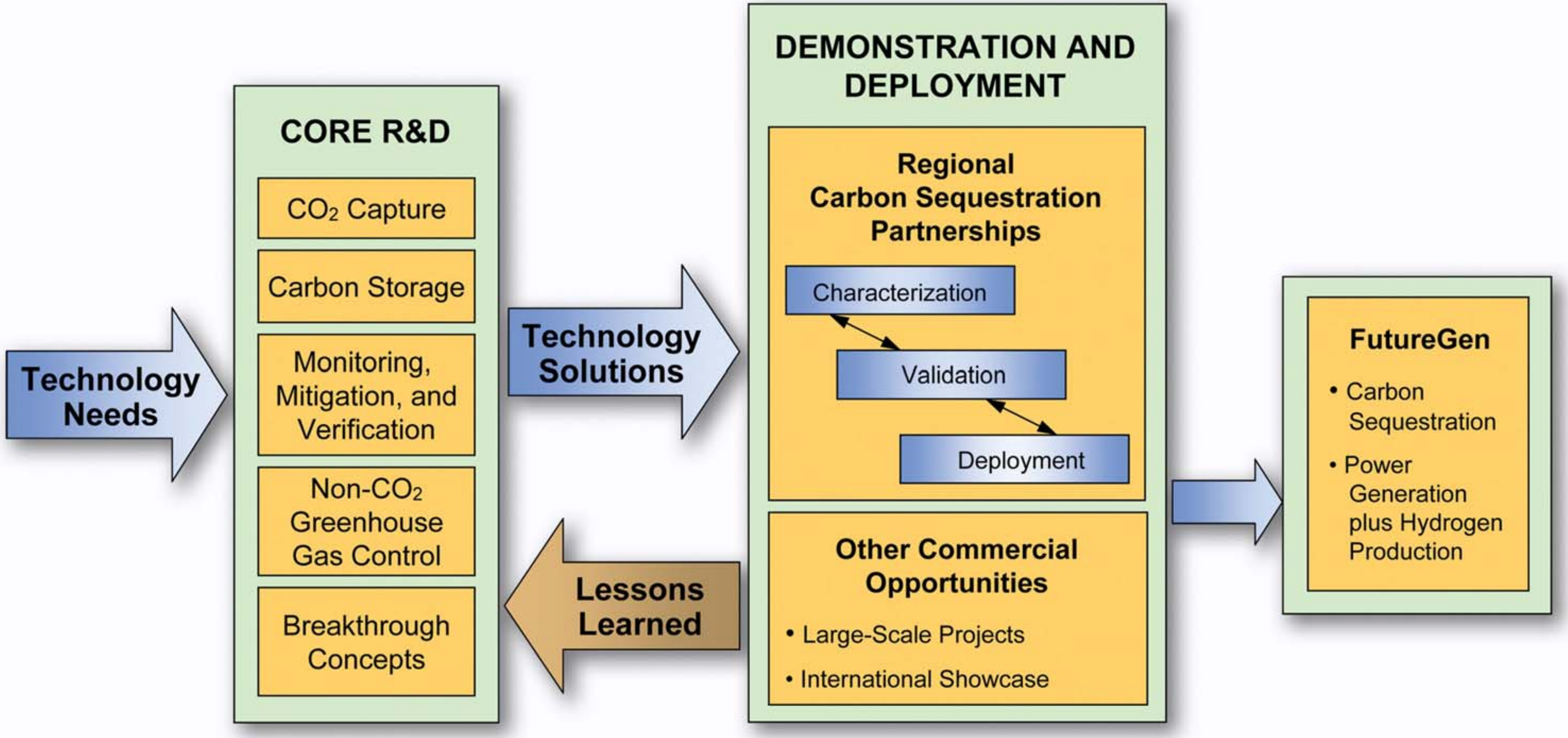
West Virginia

Alaska

Oklahoma

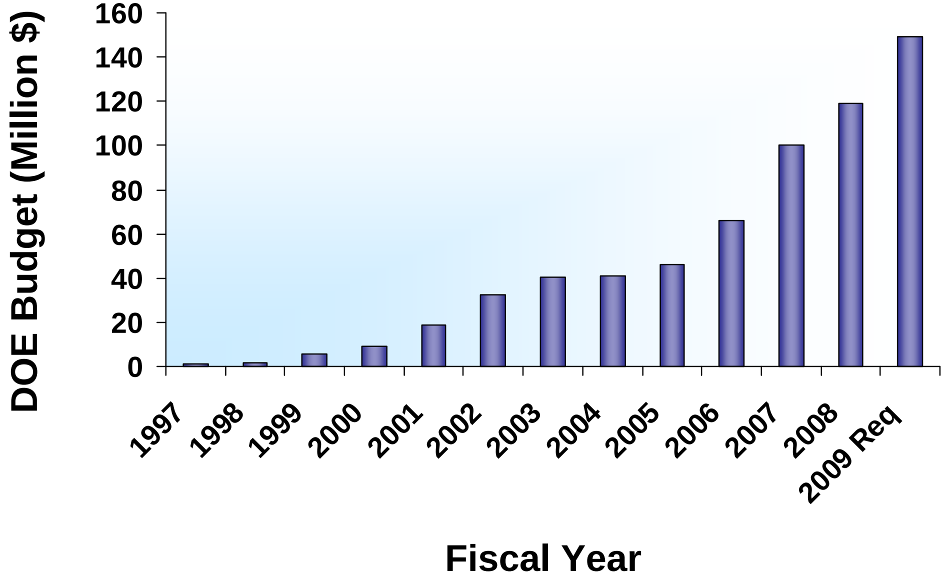
NETL

Carbon Sequestration Program Structure



T. Fout, March. 2008

Sequestration Program Statistics FY2008



Strong industry support

~ 39% cost share on projects

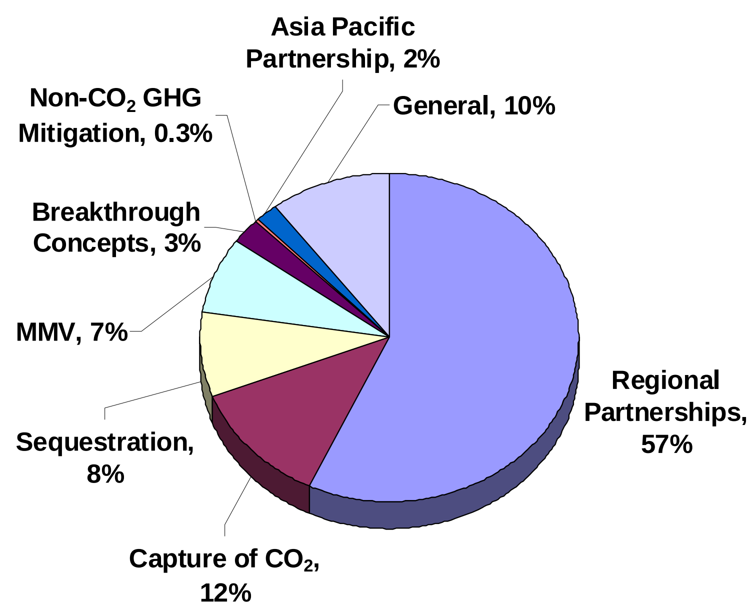
Federal Investment to Date

~ $481 Million

Diverse research portfolio

~ 70 Active R&D Projects

FY 2008 Budget

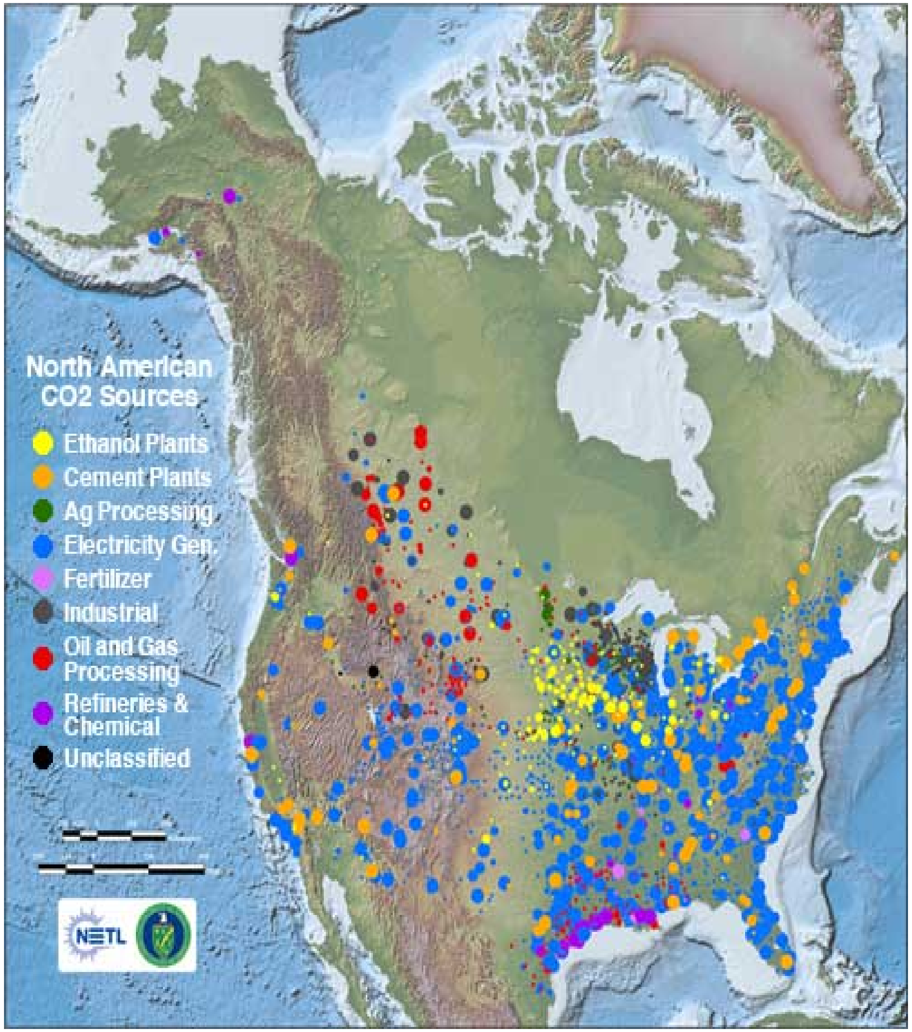


Regional Carbon Sequestration Partnerships
"Developing the Infrastructure for Wide Scale Deployment"

Characterization Phase
- **24 months (2003-2005)**
- **7 Partnerships (40 states)**
- **~$15M DOE funds**

Validation Phase
- **4 years (2005 - 2009)**
- **Field validation tests**
  - 25 Geologic
  - 11 Terrestrial
- **~$110M DOE funds**

Deployment Phase
- **10 years (2008-2017)**
- **Several large volume injection tests**



National Atlas Highlights

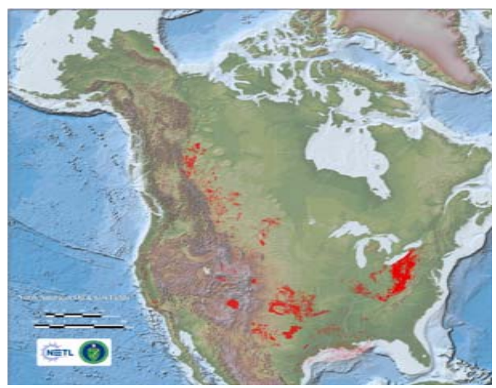
CO_2 Sources (Giga Tons)

	CO_2 Emission	Number of Facilities
CO_2 Sources	3.81	4,365

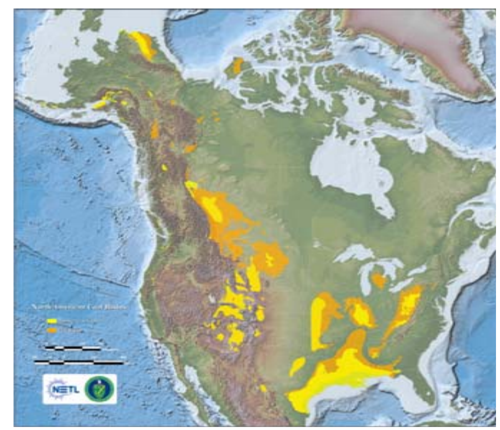
North American CO_2 Storage Potential (Giga Tons)

Sink Type	Low	High
Saline Formations	969	3,223
Unmineable Coal Seams	70	97
Oil and Gas Fields	82	83

Saline Formations



Unmineable Coal Seams



Oil and Gas Fields

Available for download at http://www.netl.doe.gov/publications/carbon_seq/refshelf.html

T. Fout,March. 2008

Innovations to Existing Plants Focuses on CO_2 Capture

- **FY08 Congressional Budget**
  - ~$36M US
  - $15 - $20 M US for CO_2 Capture and Compression

- **FY09 Presidential Budget Request**
  - $40 M US for CO_2 Capture and Compression, and Water Utilization

- **Focus on Technologies for Existing Pulverized Coal-fired Power Plants**

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FINANCIAL ASSISTANCE
FUNDING OPPORTUNITY ANNOUNCEMENT

U. S. Department of Energy

National Energy Technology Laboratory

Carbon Dioxide Capture And Separation Technology Development For Application To Existing Pulverized Coal-Fired Power Plants

Funding Opportunity Number: DE-PS26-08NT00134

Announcement Type: AMENDMENT 02

CFDA Number: 81.089 Fossil Energy Research and Development

Issue Date of Amendment 01:	February 15, 2008
Letter of Intent Due Date:	Not Applicable
Pre-Application Due Date:	Not Applicable
Application Due Date:	April 10, 2008 at 8:00:00 PM Eastern Time

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Technology Pathways
Separation & Capture of CO_2

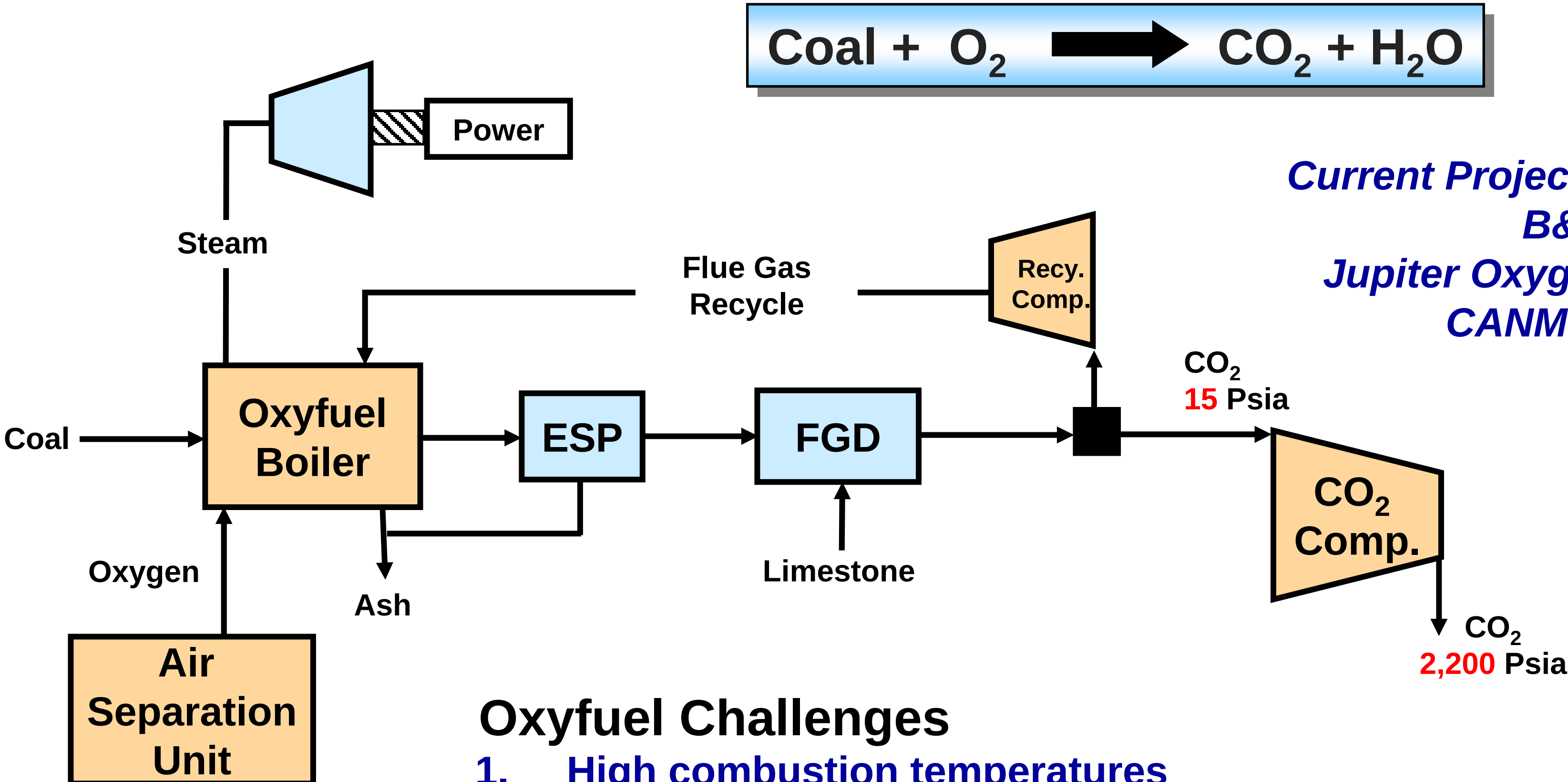
Issue

- Demonstrated technology is costly

Pathways

- Post-combustion capture
- Pre-combustion capture
- Oxycombustion
  - Chemical looping

Pulverized Coal Oxycombustion



Current Projects:
B&W
Jupiter Oxygen
CANMET

Oxyfuel Challenges

1. **High combustion temperatures**
   *Boiler materials of construction issues
   *Requires large amounts of flue gas recycle
2. **Cryogenic oxygen production is expensive and energy intensive**
   *Opportunity for oxygen membranes

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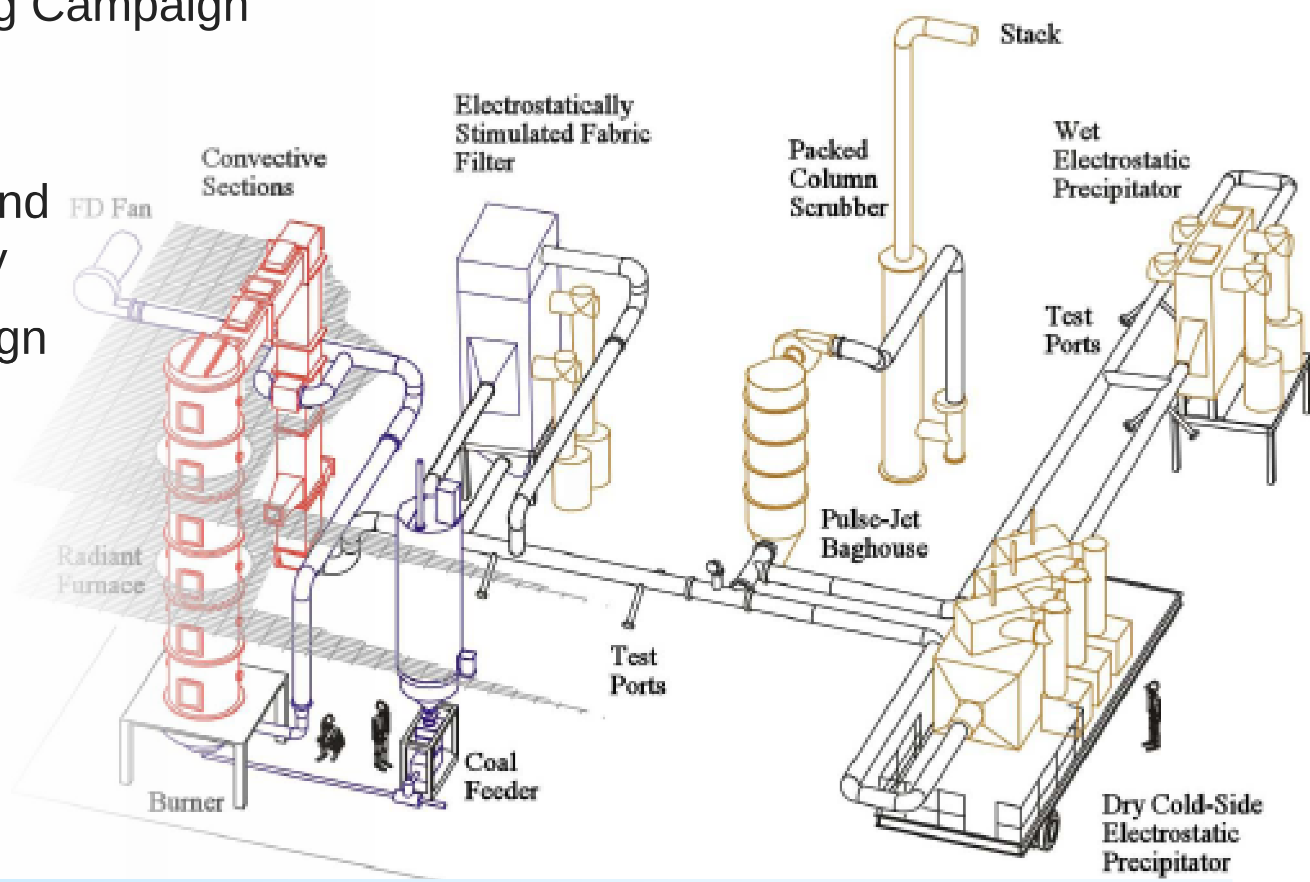
Oxygen-Fired CO_2 Recycle for Application to Direct CO_2 Capture from Coal-Fired Power Plants

- **Retrofit existing combustion facility for oxy-combustion**
  - Design and Install Recycle Loop
  - Parametric Testing Campaign
- **Status (1/2008):**
  - Added partners Doosan Babcock and Southern Company
  - Recycle Loop Design Completed
  - Oxy-combustion Burner Completed
  - Baseline CFD completed



Participants: Southern Research Institute, Maxon, DTE Energy, The BOC Group, Doosan Babcock, Southern Company, REI

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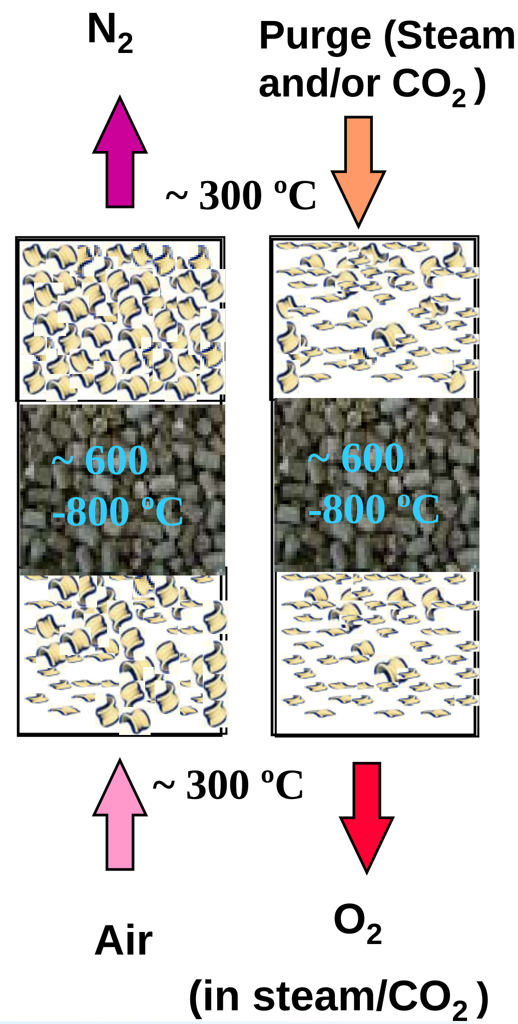
Ceramic Autothermal Recovery

- Process Features
  - Uses oxygen "storage" property of perovskites at high temperatures. Highly selective O_2 extraction.
- Project Status (12/31/2007)
  - Determined acceptable sulfur levels for PDU
  - Determining effects of sulfur exposure to perovskites (short and long term)
  - Systems analysis and economic study to determine effects of sulfur removal on process economics

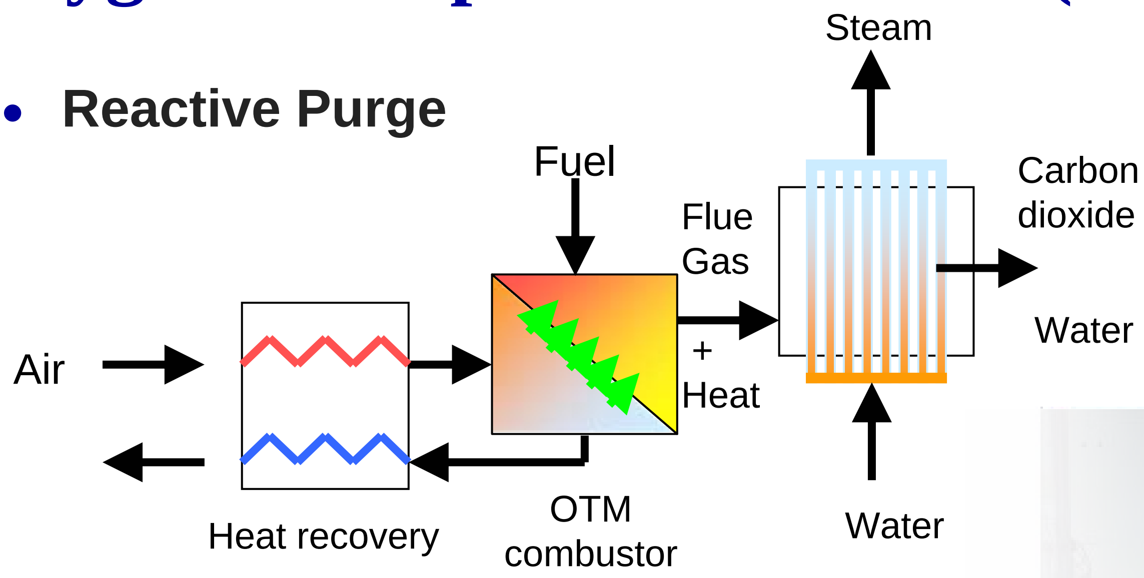
Perovskite Samples



Participants: Linde (BOC), Alstom, WRI

Oxygen Transport Membranes (OTM)

- **Reactive Purge**



- **Project Status (12/31/07):**
  - Conducting Systems analysis of Coal-based Concepts
  - Investigating Freeze-casting of porous supports
  - Constructed High Pressure Reactor

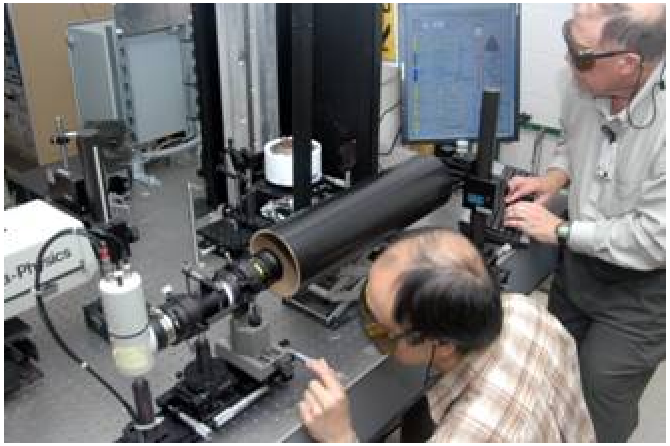
Participants: Praxair, University of Utah

Graphic from Praxair Presentation, 2/15/06 NETL Pittsburgh

NETL/Office of Research and Development Oxy-Combustion Activities

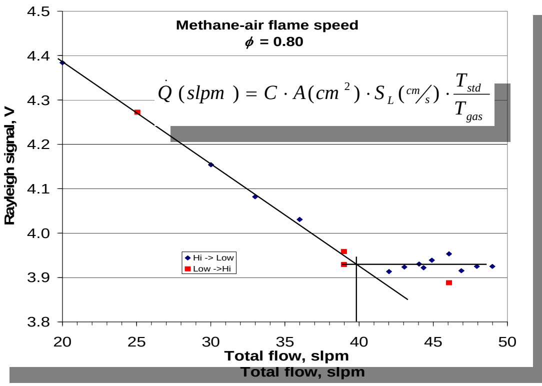
- **PC Coal and Turbine Power Cycles**

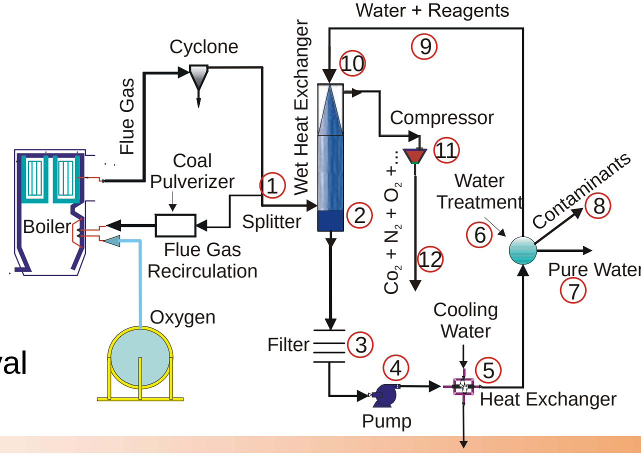
  Overall objective: development of improved and validated modeling tools for oxy-combustion systems



- **Approach combines modeling, lab tests, and field work**

Measurement of Oxy-Fuel Laminar Flame Speeds

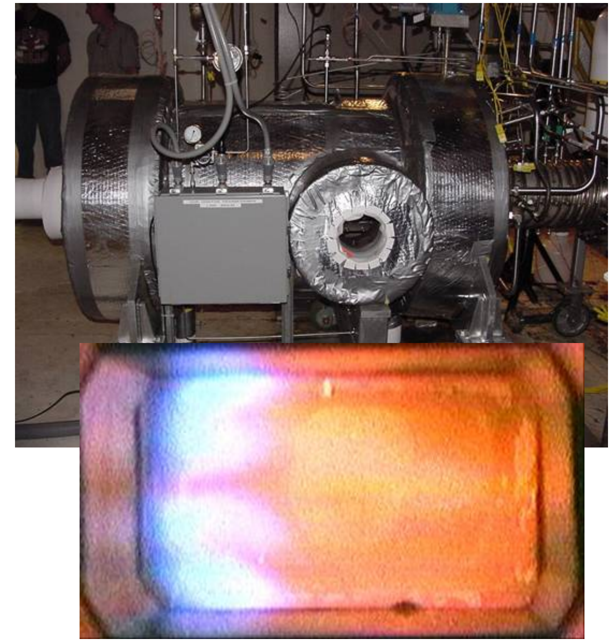




The Integrated Pollutant Removal (IPR) Process for CO2 Capture

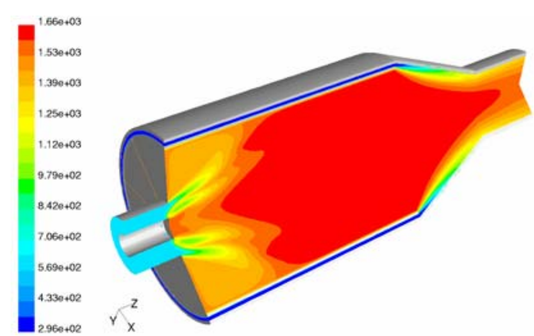
NETL/Office of Research and Development Oxy-Combustion Activities – cont'd

- **Obtain fundamental combustion data and radiative properties of oxy-flames**
  - Laminar flame speeds
  - Radiative properties/heat transfer in high steam environments and validation data sets
- **Systems-level modeling –**
  - test, demonstration and full scales Develop improved modeling/ simulation tools
- **Develop and validate CFD models for oxy-fired PC combustion**
- **Assess materials performance in oxy-combustion environments**
- **Develop approaches to capture CO_2 from oxy-fuel combustion products**



Reheat Combustor Demonstration

– NETL/NASA/CES



Study Matrix

Case	CO_2 Capture	Steam psig/°F/°F	Oxidant	NOx Control	CO_2 Purity	Storage
1	None	3500/1110/1150[a]	Air	0.07 lb/10^6Btu - Low NOx Burners - Over-fired Air - SCR	N/A	Saline Formation
2	None	4000/1350/1400[b]			N/A	
3	Econamine	3500/1110/1150			~100%	
4	Econamine	4000/1350/1400			~100%	
5	Cryogenic ASU Oxyfuel	Supercritical 3500/1110/1150	95 mol% O_2	0.07 lb/10^6Btu - Low NOx Burners - Over-fired Air - Flue Gas Recycle	Spec. A	
5A			99 mol% O_2		Spec. B	
5B			95 mol% O_2		Spec. B*	
5C			95 mol% O_2		Spec. C	
6	Cryogenic ASU Oxyfuel	Ultrasupercritical 4000/1350/1400	95 mol% O_2		Spec. A	
6A					Spec. C	
7	Membrane ASU Oxyfuel	Supercritical 3500/1110/1150	~100 mol% O_2		Spec. B	
7A					Spec C	

[a]Steam conditions for the supercritical (SC) power plant cases (available now)
[b]Steam conditions for the ultra-supercritical (USC) power plant cases (2015-2020)

ASU: Air Separation Unit
SCR: Selective Catalytic Reduction

CO_2 Purity

Specification A: Raw flue gas product using 95 mol% oxygen → Saline Formation
Specification B: Raw flue gas product using 99 mol% oxygen → Saline Formation
Specification C: Raw flue gas product using 95 mol% oxygen and treated to meet EOR Spec.

	EOR	Saline Formation
Pressure (psia)	2200	2200
CO_2	>95 vol%	not limited[1]
Water	dehydration[2] (0.015 vol%)	dehydration[2] (0.015 vol%)
N_2	<4 vol%	not limited[1]
O_2	<40 ppmv	<100 ppmv
Ar	< 10 ppmv	not limited
NH_3	<10 ppmv	not limited
CO	< 10 ppmv	not limited
Hydrocarbons	<5 vol%	<5 vol%
H_2S	<1.3 vol%	<1.3 vol%
CH_4	<0.8 vol%	<0.8 vol%
H_2	uncertain	uncertain
SO_2	<40 ppmv	<3 vol%
NOx	uncertain	uncertain

1: These are not limited, but their impacts on compression power and equipment cost need to be considered.
2: Dehydration process, such as a glycol absorber, is required.

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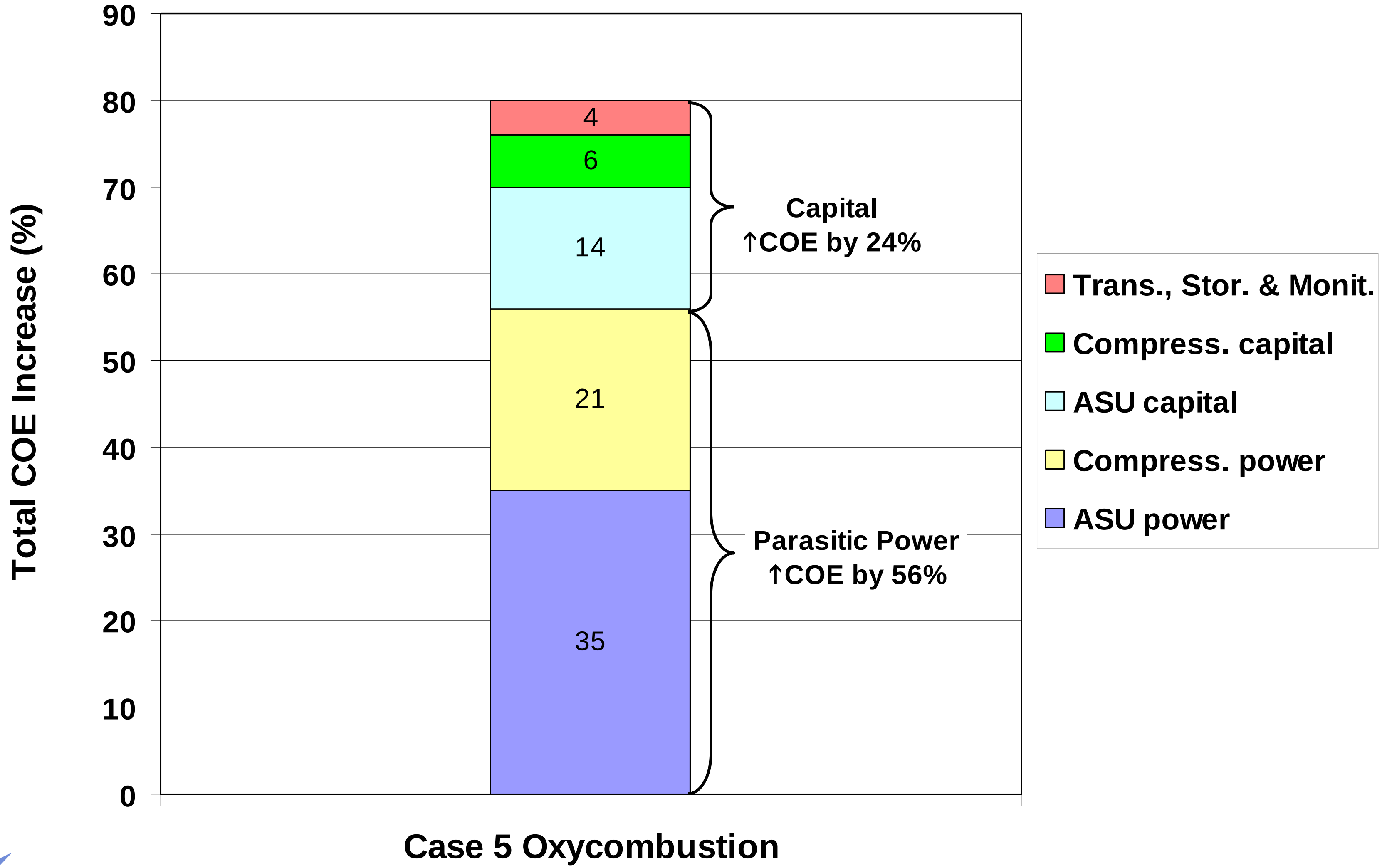
Supercritical Oxyfuel Combustion
Key Points

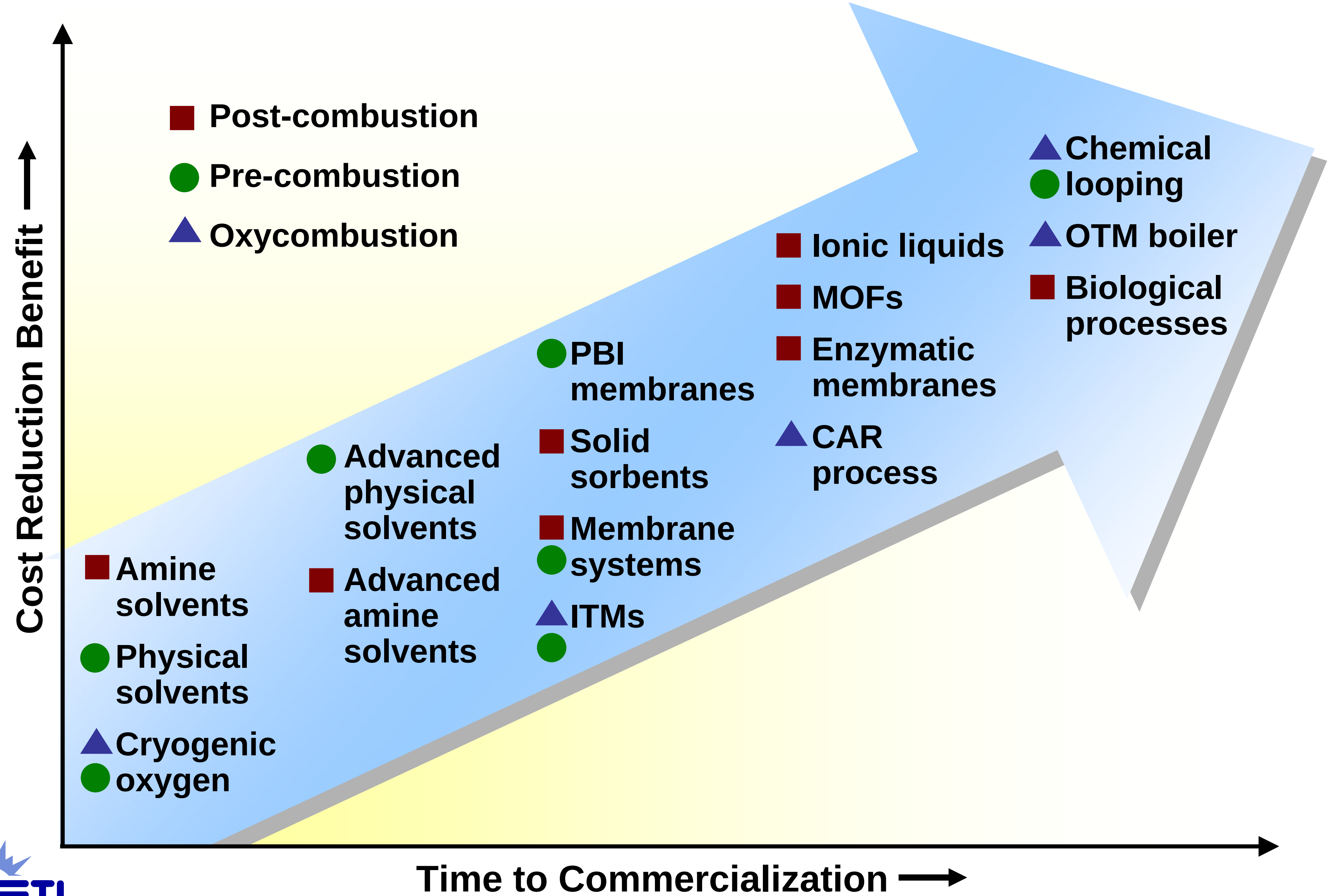
- **Going from 95% to 99% O_2 purity results in:**
  - Less than 0.5% increase in ASU auxiliary load (130.5 MW to 131 MW)
  - A 9% increase in ASU capital cost ($509/kWe to $555/kWe)
  - A 4 Megawatt decrease in CO_2 compression and purification auxiliary power (78.5 to 74.5 MW) → Results in a slightly higher net power plant efficiency.

Bottom Line: The CO_2 compression and purification auxiliary power savings—due to the use of a higher purity oxidant—is offset by a 9% increase in ASU capital cost resulting in a negligible advantage in going from 95 to 99% oxygen purity.

Oxyfuel COE Increase Distribution



Innovation Advances



T. Fout, March. 2008

Figueroa JD, et al., *Advances in CO_2 Capture Technology—The U.S. Department of Energy's Carbon Sequestration Program, Int. J. Greenhouse Gas Control*, 2007

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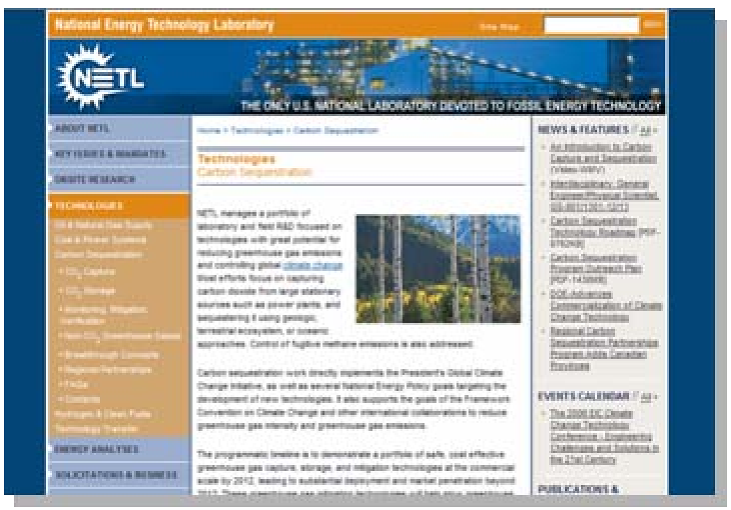

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United States
Environmental Protection
Agency

Understanding the Potential Environmental Impacts of Oxy-fuel Combustion

C.W. Lee and C. Andrew Miller

Office of Research and Development
National Risk Management Research Laboratory, Air Pollution Prevention and Control Division

March 5, 2008

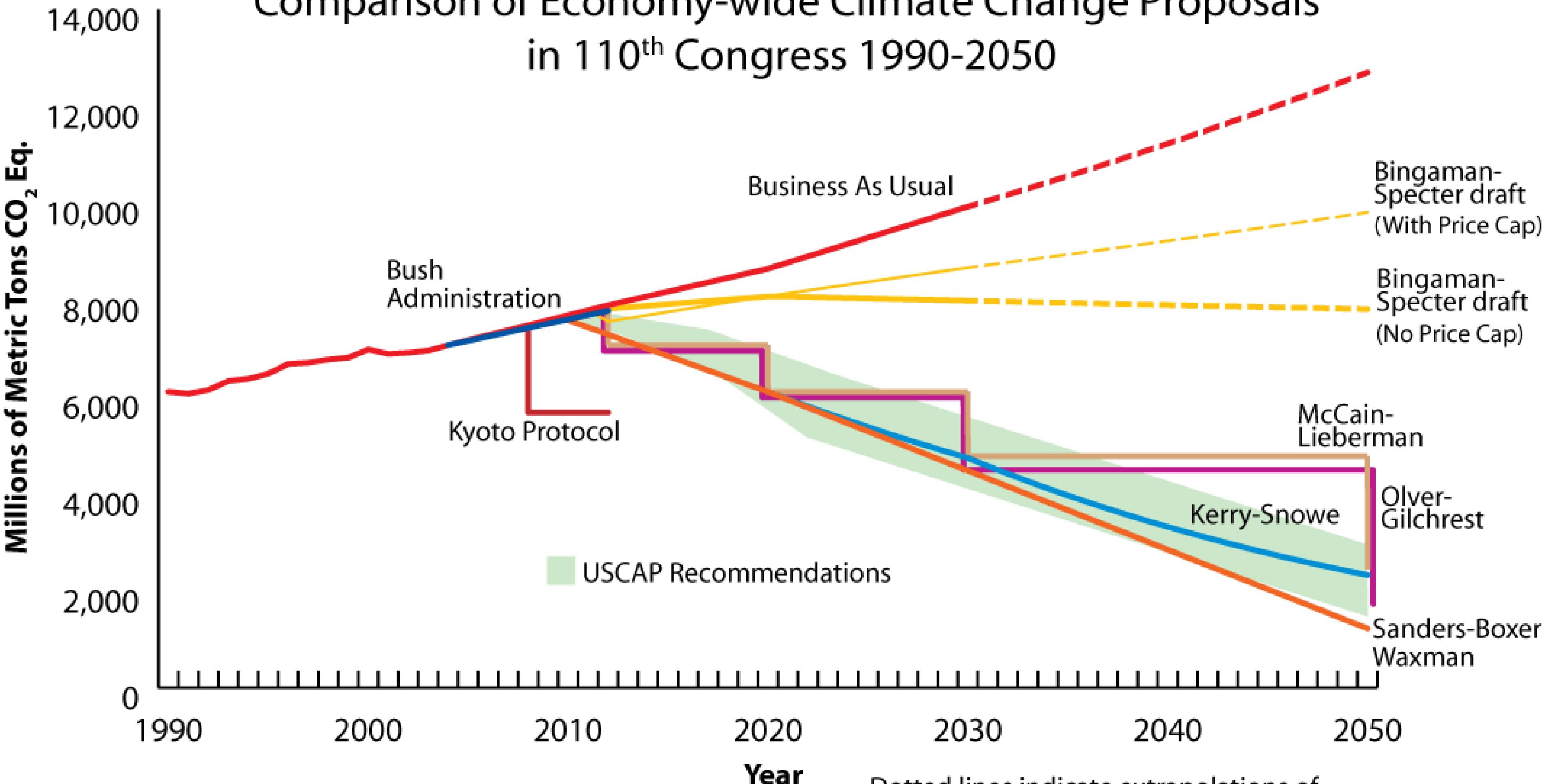
EPA
United States
Environmental Protection
Agency

Legislative and Regulatory Context

- Recent Supreme Court Decision
  - EPA has statutory authority to regulate GHG emissions
  - EPA must make a “reasoned decision” based on analysis of potential endangerment from GHGs
- Several bills proposed in current Congress
- Energy Independence and Security Act (2007)
  - Calls for R&D of new and advanced technologies for the separation of oxygen from air
  - Authorized (not allocated) $200,000,000/yr for capture research, development & demonstration

EPA
United States
Environmental Protection
Agency

Comparison of Economy-wide Climate Change Proposals in 110th Congress 1990-2050



WORLD RESOURCES INSTITUTE

Dotted lines indicate extrapolations of Energy Information Administration projections

Modified: May 10, 2007

Environmental Issues of Concern

- EPA is responsible for addressing environmental issues and impacts, including:
  - CO_2 emissions and effects
  - Impacts of geological sequestration
  - Other environmental impacts
    - SO_2, NO_x, Hg, other pollutants
    - Solid and liquid effluents
  - Application of carbon capture and sequestration to non-utility sectors

United States Environmental Protection Agency

Key EPA Questions

- Currently many more questions than answers
- Ability to be applied as retrofit technology
- Applicability to other sectors
- Parasitic power requirements
- Scalability
- CO_2 transport and storage requirements
- Fate of effluents

United States Environmental Protection Agency

Oxy-fuel Combustion as Retrofit Technology

- Enormous investment in current fossil-fuel power generation system
- Ability to retrofit existing plants may provide an attractive alternative to requiring new plants to be built
- Need to understand capital and operating costs, retrofit time, operational issues, emission characteristics and potential environmental impacts (to air, water, soil)
- What differences (if any) exist between retrofit and new installations?

Applicability to Non-Utility Sectors

- Can oxy-fuel combustion be used in other sectors (e.g. cement industry)?
  - As retrofit, or as new installation only?
- What are costs, operating issues, and emissions associated with these applications?
- How do they differ from current technologies?

United States Environmental Protection Agency

Operability and Technology Scalability

- Need to understand parastic power to estimate potential changes in demand and supply of electricity, and therefore potential changes in emissions
  - Need to understand how to evaluate fuel requirements and mass of potential effluent streams per unit of net electric power
- What is the range of plant sizes for which oxy-fuel combustion is practical?
- How well does oxy-fuel combustion adapt to different operating conditions, such as changes in coal type?

United States Environmental Protection Agency

CO_2 Transport and Storage Requirements

- Post-combustion CO_2 separation and compression will result in different CO_2 stream composition than oxy-fuel combustion
  - Does this make a difference to transport and storage?
  - Current transport assumes very high purity CO_2
  - Existing specifications for CO_2 properties based on corrosion potential of pipelines
  - Significant changes to CO_2 stream purity may result in need for more expensive pipeline material
  - Need to understand impacts of CO_2 composition on reservoir

EPA United States Environmental Protection Agency

U.S. CO_2 Pipeline Quality Specifications

Component	Limit		Comments
CO_2	95%	Min	MMP* Concern
Oxygen	10 ppm	Max	Corrosion
Temperature	120 deg F	Max	Materials
Glycol	0.3 gal/MMcf	Max	Operations
H_2S	10 – 200 ppm	Max	Safety
Water	30 lbs/MMcf	Max	Corrosion
Hydrocarbons	5%	Max	MMP Concern
Nitrogen	4%	Max	MMP Concern

*Minimum miscibility pressure

Efforts at EPA – Current and Potential

- Currently evaluating existing literature on oxy-fuel combustion, demonstrations of CO_2 transport and sequestration
- EPA has flexible pilot-scale facilities for conducting tests of oxy-fuel combustion with natural gas, fuel oil, and coal
- Also have extensive experience in combustion exhaust chemistry analyses, including trace elements such as Hg

Technical Challenges

- Flue gas recirculation
  - –Can SO_2 and PM be removed to a high enough degree to avoid excessive fan corrosion?
- Trace element content
  - –What are the implications for presence of Cl, Hg?
- Verification of CO_2 and impurity behavior at supercritical conditions
  - –Conventional measurement methods not applicable in current configuration

EPA
United States
Environmental Protection
Agency

Potential Goals of EPA Research

- Evaluation of gaseous, solid, and liquid effluent streams
  - To what degree do these differ from current effluents?
  - Do the differences have environmental implications (either positive or negative)?
- Understanding operational issues, including startup, shutdown, and transient operation, that may have environmental impacts

3rd Workshop IEAGHG Oxy-Combustion Network, Yokohama, March 2008

HIGH TEMPERATURE REDUCTION OF NITROGEN OXIDES

Fredrik Normann

Chalmers University of Technology

Chalmers Oxy-Fuel Research

Purpose: Obtain knowledge for commercial oxy-fuel boilers

Progress of work:

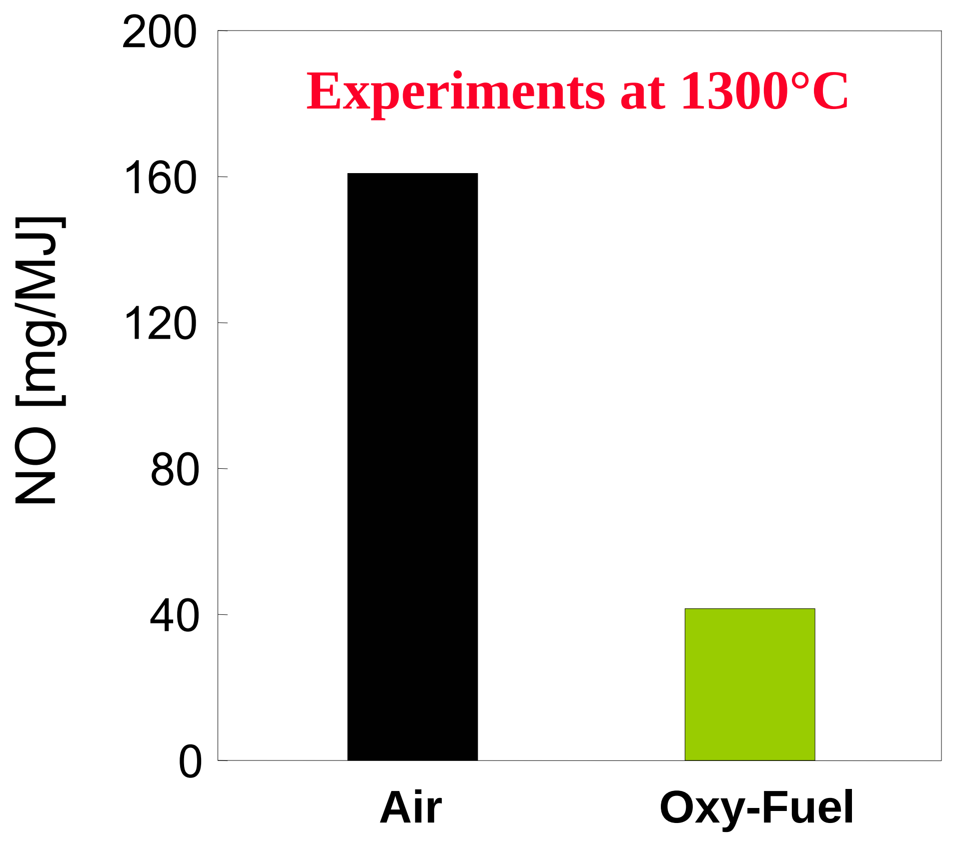
- Build a 100 kW test unit
- Operation with propane
- Operation with lignite

Content of work:

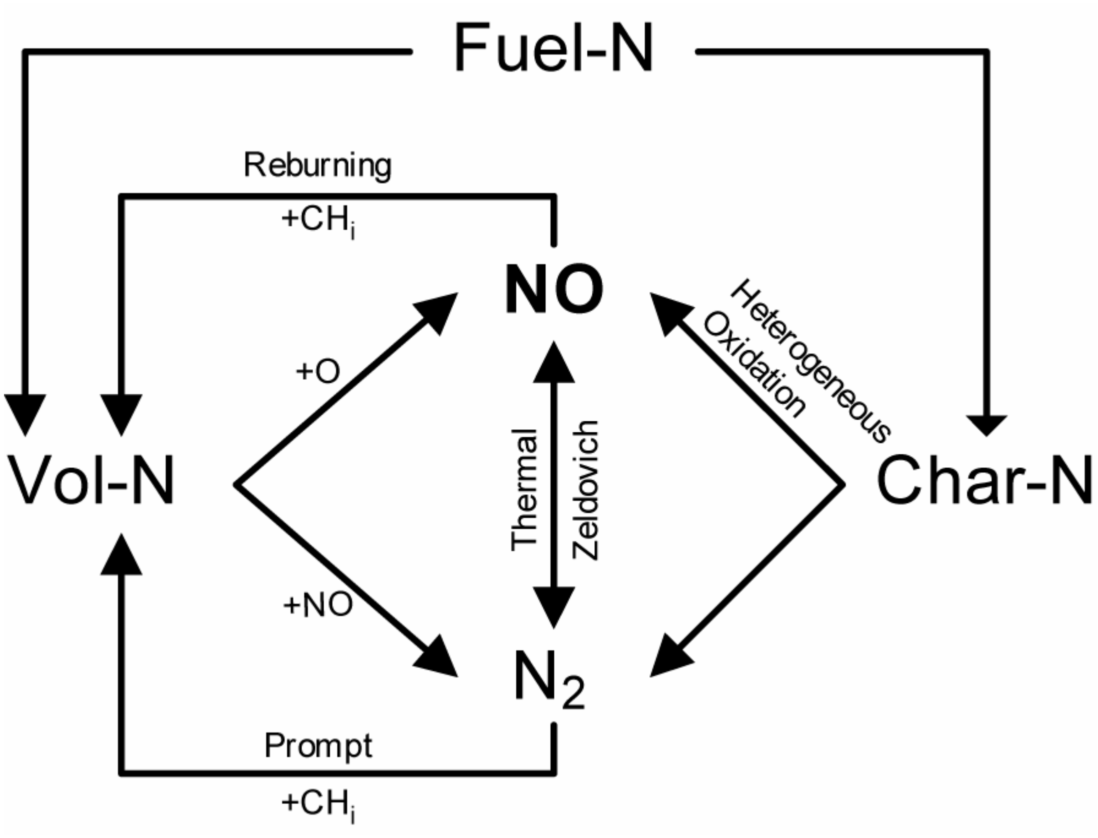
- Heat transfer
- Emissions

Present presentation: High temperature reduction of NO_x

NO Emission



Nitrogen Chemistry



Nitrogen Chemistry

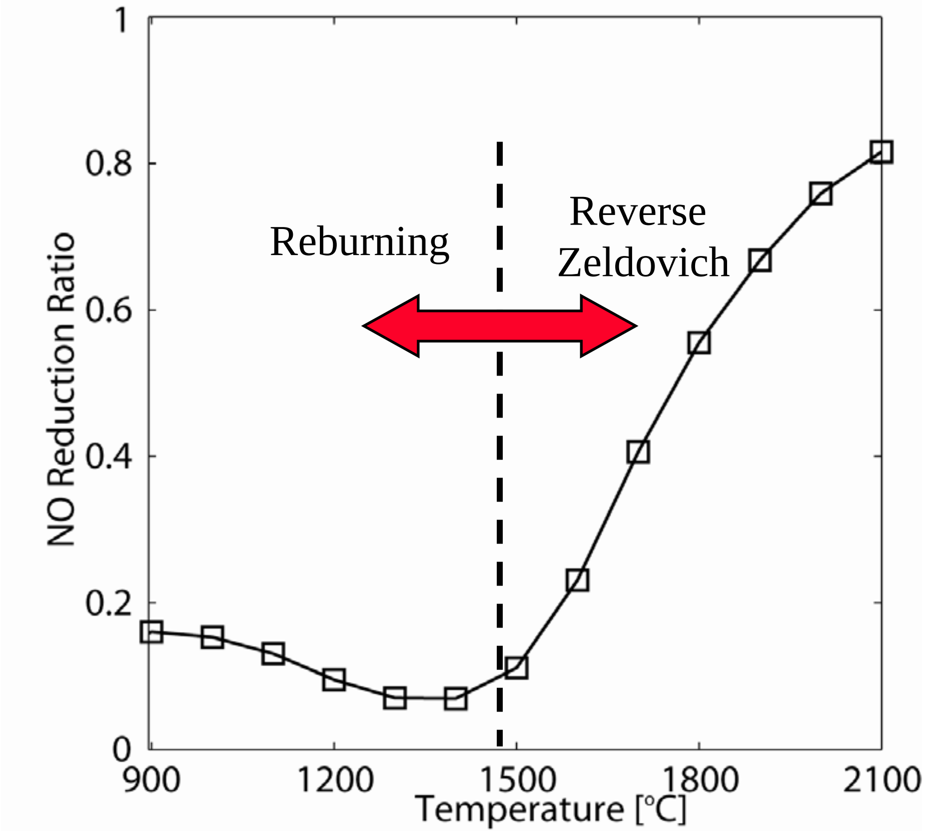
$$O_2 + N_2 \underset{\text{Zeldovich}}{\overset{\text{Thermal}}{\longleftrightarrow}} 2\,NO$$

Method

- Detailed gas phase reaction mechanism
- Isothermal plug flow reactor
- Methane flame
- HCN and NH_3 as Fuel-N

NO Reduction

- NO_{in} = 1000ppm
- N_{2in} = 0%
- t = 1 s
- λ = 0.9
- No Fuel-N

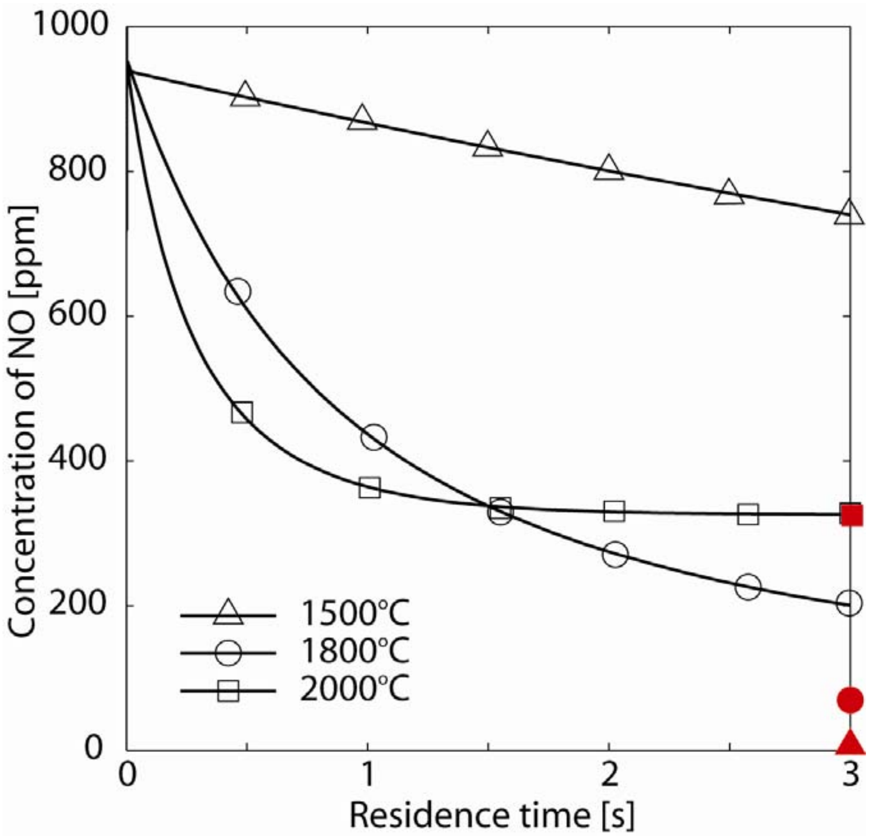


Aim

Investigate possibilities for high-temperature reduction of NO_x:

- The influence of combustion parameters and their limits
- The implementation for an oxy-fuel combustion boiler

Residence Time

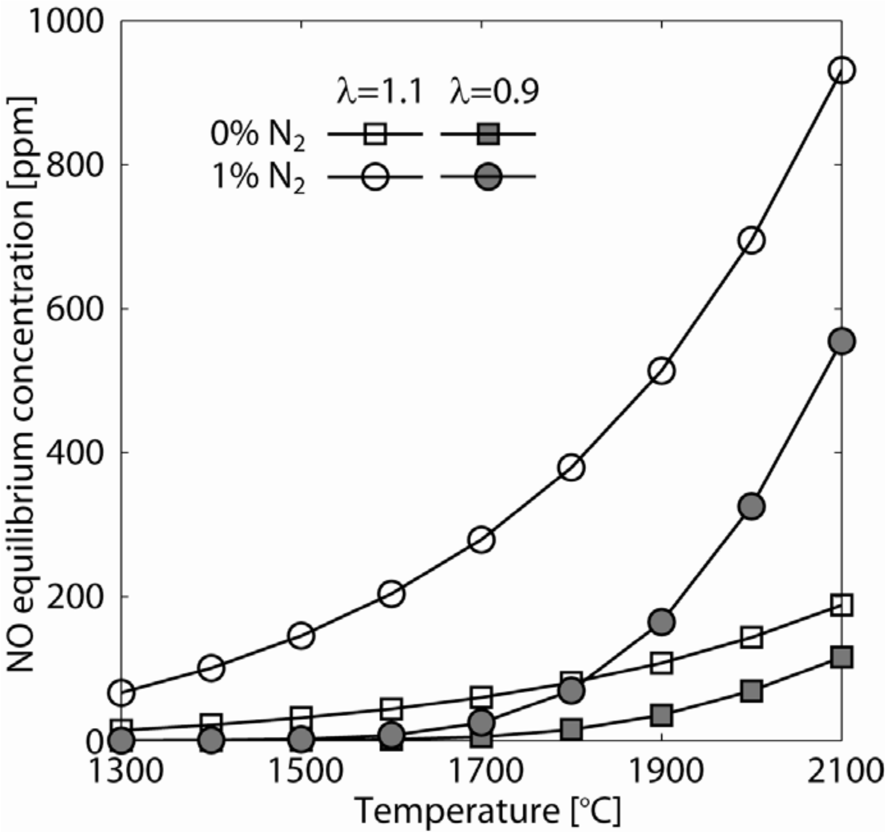


- NO_{in} = 1000ppm
- N_{2in} = 1%
- λ = 0.9
- No Fuel-N

Equilibrium Concentration

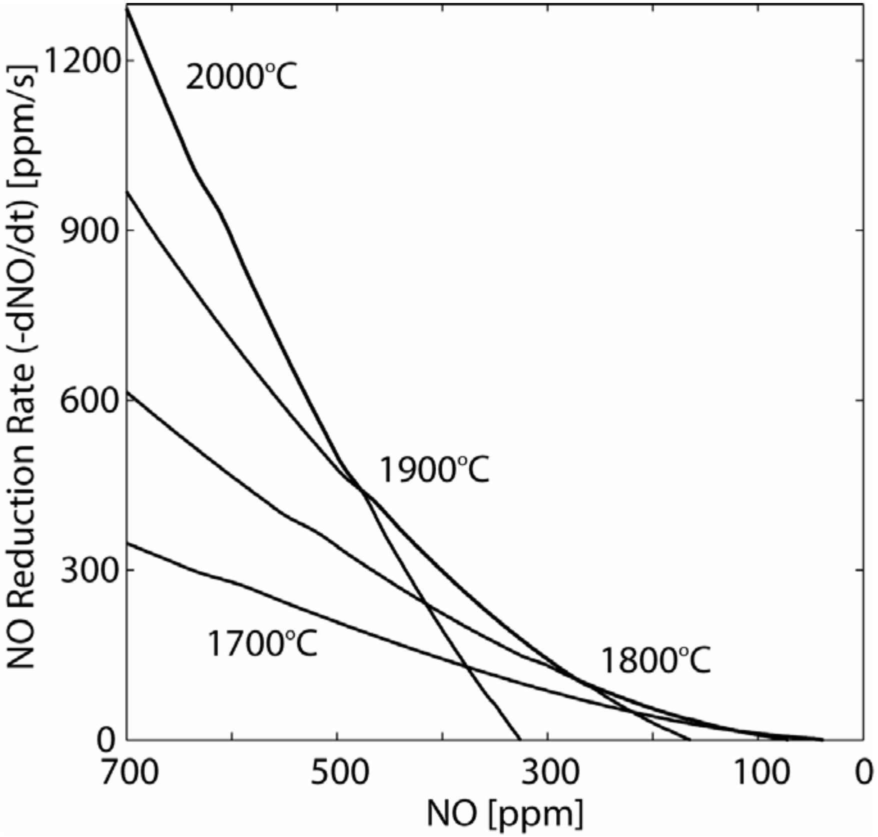
Gas Phase Reduction Limits

- NO_{in} = 1000ppm
- No Fuel-N



Temperature Optimization

- NO_{in} = 1000ppm
- N_{2in} = 1%
- λ = 0.9
- No Fuel-N



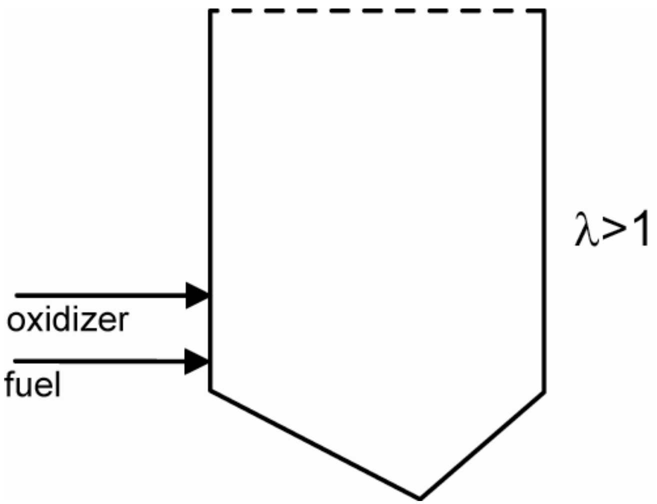
Design considerations

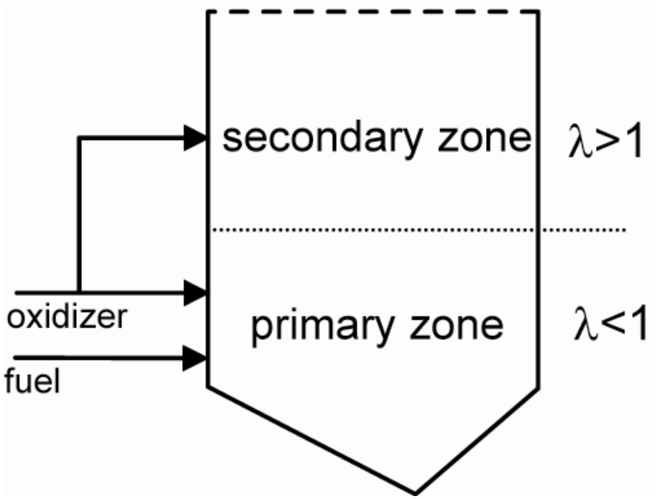
- Low concentrations of N_2 and O_2
- High temperature
- Long residence time

Firing Strategies

Staged Combustion –

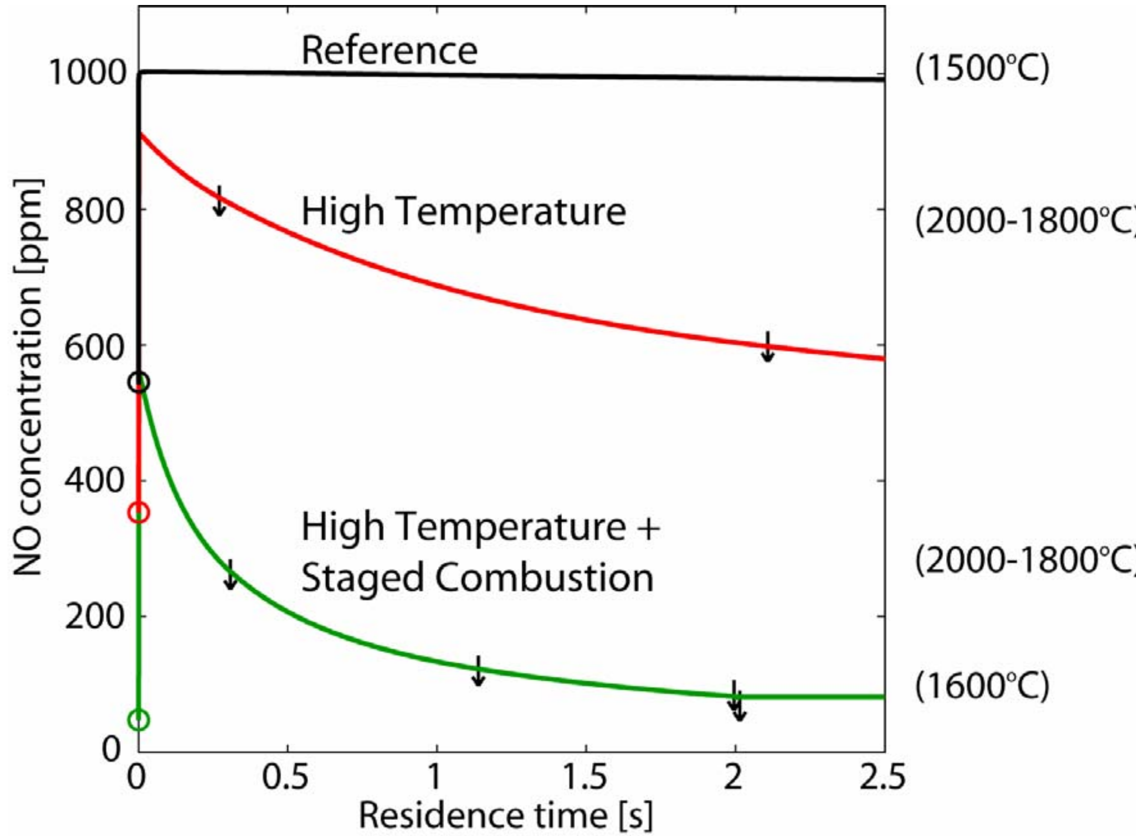
Low concentration of O_2 in the combustion zone





Firing Strategies

- Fuel-N
- True Recycle



High-Temperature Combustion

Oxygen-enriched combustion –

- Higher combustion temperature
- Lower mass flow through the furnace

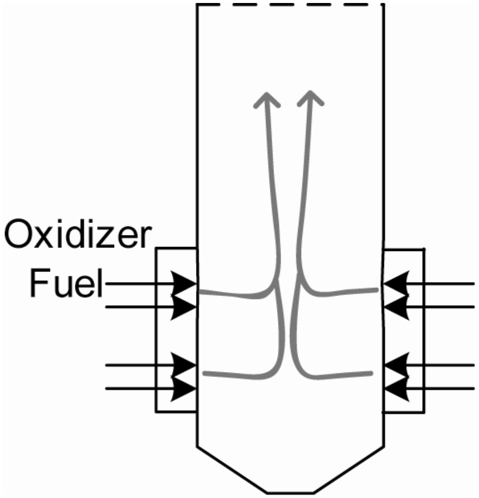
High-Temperature Combustion

Other Combustion Issues -

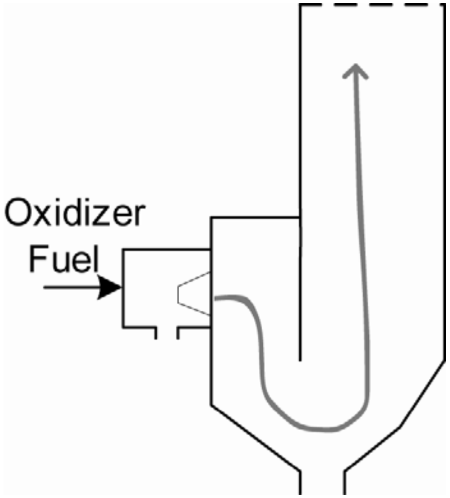
- Unburned Carbon
- Ash Melting/ Slagging
- Heat Transfer
- Corrosion

High-Temperature Combustion Systems

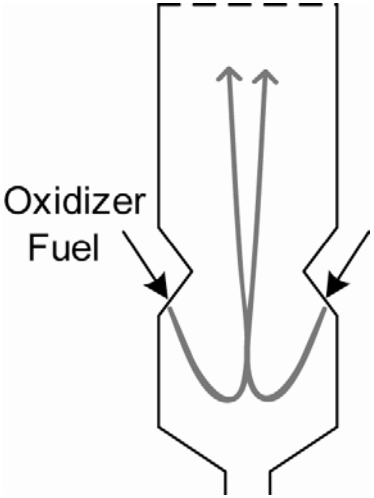
Rapid mixing burners –



Cell Burner



Cyclone Burner



Downshot Burner

Conclusions

- Limited by Equilibrium and Reaction Rate
  - Low air ingress and High oxygen purity
  - Sub-stoichiometric combustion zone
  - High but decreasing temperature
  - Long residence time
- Available Techniques
  - High-temperature combustion systems
  - WBB

Understanding the Effects of O_2 and CO_2 on NOx Formation during Oxy-Coal Combustion

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3rd IEA Greenhouse Gas Workshop on Oxy-Fuel Combustion
Yokohama, Japan
March 4-6, 2008

Overview of Oxy-Coal NOx Research

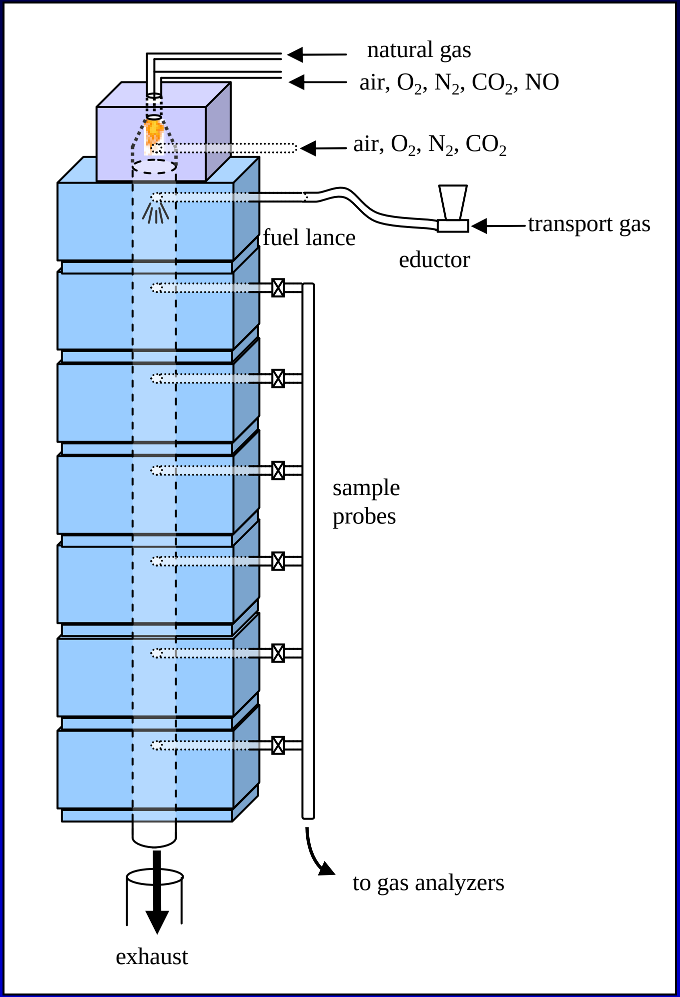
- **Many burner studies on char burnout (LOI) and NO_x and SO_2 emissions during oxy-coal combustion**
- **Most studies find significantly lower NOx emissions during oxy-coal combustion (~ 3X reduction)**
  - ✓ **Negligible thermal NOx production (no N_2 in oxidizer)**
  - ✓ **Reburn of recycled NOx in coal flame**
  - ✓ **Reburn of recycled NOx on coal char**
- **So far, few systematic studies to understand relative contributions of these effects or to determine direct effects from different O_2 and CO_2 concentrations**
  - ✓ **Okazaki and Ando, 1997, a notable exception**

Goal of Present Study

Determine effect of gas environment on NOx formation from combustion of coal and coal char when burned as *dispersed, low concentration* particles (burn as isolated particles)

- ✓ **vary O_2 concentration (with little O_2 consumption)**
- ✓ **vary background bulk gas (N_2 or CO_2)**
- ✓ **vary background NO (affecting NO reburn)**
- ✓ **control temperature**

Experimental Setup: Multifuel Combustor



- 1 atm
- 150 mm dia, 4.2 m long SiC reaction tube with 7 independently controlled heater sections (up to 1350 °C)
- operates on air or specified mixtures of O_2 with N_2 or CO_2
- natural gas burner to preheat gases
- coal or char particles introduced at top of reactor
- Horiba CEM and micro-GC analysis of stable gases

Pulverized Coal and Char Properties

	Coal Type				Char	
	Pittsburgh Bailey		Black Thunder		Pittsburgh Bailey	
Proximate	wt%, as rec'd	wt% dry	wt%, as rec'd	wt% dry	wt%, as rec'd	wt% dry
moisture	1.4		10.8		1.1	
ash	6.9	7.0	5.0	5.6	19.4	19.6
volatiles	35.4	35.9	40.4	45.3	3.3	3.3
fixed C	56.3	57.1	43.8	49.1	76.2	77.0

Ultimate	wt% dry	wt% DAF	wt% dry	wt% DAF	wt% dry	wt% DAF
C	77.2	82.9	60.9	64.1	76.9	95.4
H	5.2	5.6	5.2	5.5	0.7	0.9
O (by diff.)	7.2	7.7	27.6	29.1	0.2	0.2
N	1.5	1.6	0.9	0.9	1.3	1.6
S	2.0	2.2	0.4	0.5	1.2	1.5

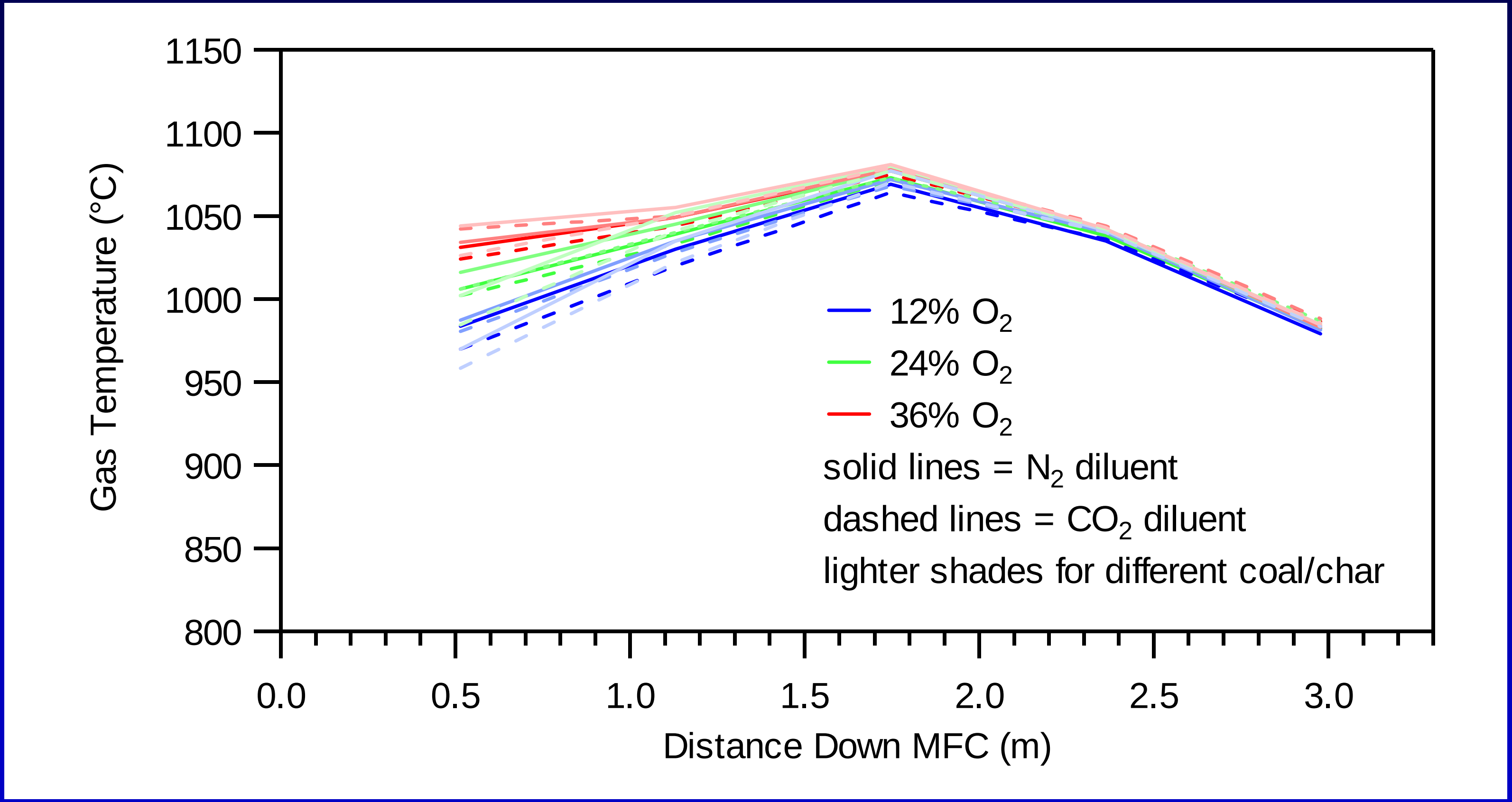
Pitt coal char was produced at 1500 K in MFC

MFC Gas Compositions Investigated

Nominal Condition	Initial Concentration (vol-%)				Final Concentration (vol-%)			
	O_2	N_2	CO_2	H_2O	O_2	N_2	CO_2	H_2O
12% O_2 in N_2	12.6	75.9	3.9	7.6	10.7	75.7	5.4	8.2
24% O_2 in N_2	25.0	63.5	3.9	7.6	21.2	63.2	6.9	8.7
36% O_2 in N_2	37.6	50.9	3.9	7.6	31.9	50.5	8.3	9.3
12% O_2 in CO_2	13.3	1.1	73.9	11.7	11.3	2.3	74.3	12.1
24% O_2 in CO_2	26.0	1.1	61.2	11.7	22.2	1.2	63.8	12.8
36% O_2 in CO_2	38.7	1.1	48.6	11.7	32.9	1.1	52.6	13.4

- ***Equivalence Ratio maintained at 0.15 for all experiments***
  - ✓ ***low solids loading, little O_2 consumption (reactor as entrained flow reactor)***
- ***Two levels of background NO investigated***
  - ✓ ***30 ppm for 'low reburn'***
  - ✓ ***530 ppm for 'high reburn'***

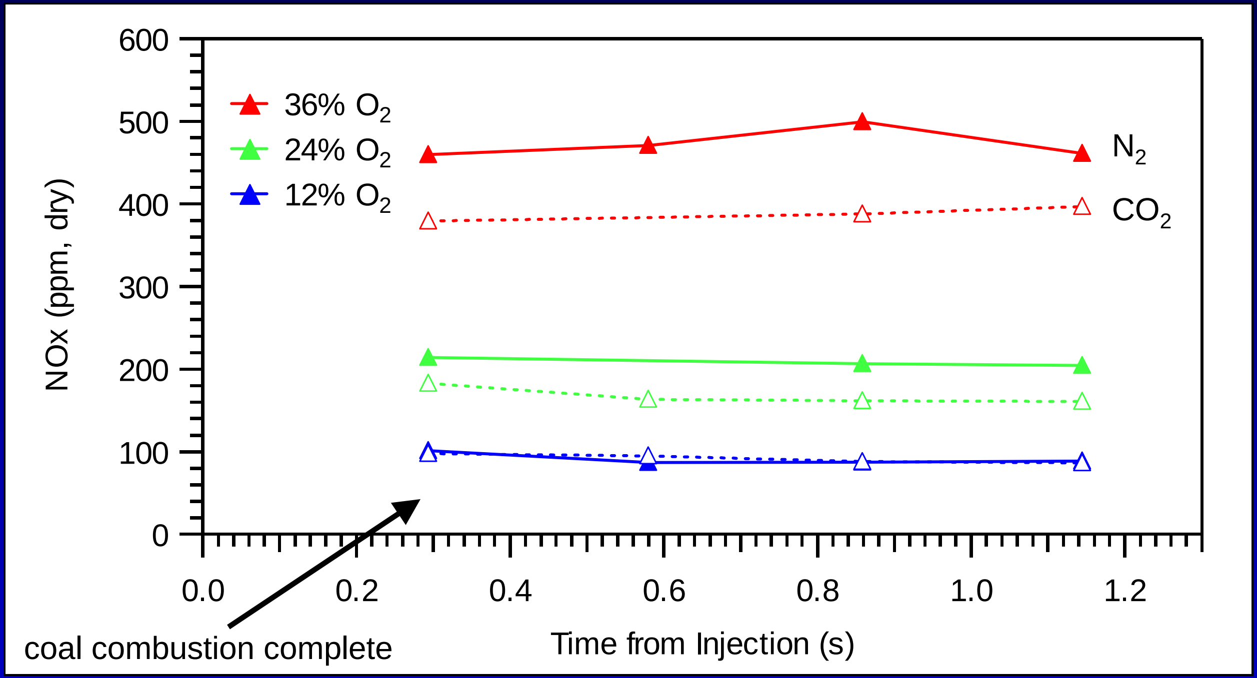
Gas Temperature Profiles (Type K thermocouples)



Nominal reactor temperature of 1050 °C for all experiments

NOx Measurements: low reburn

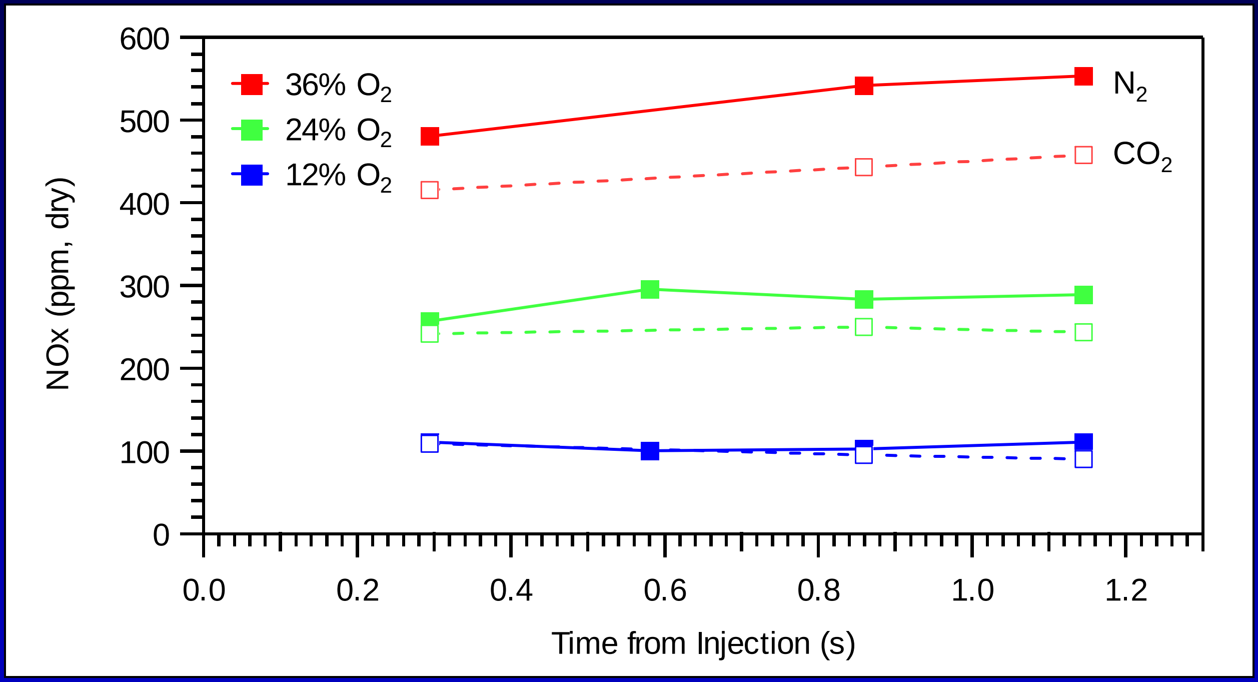
Pittsburgh coal



- ***NOx production favored at higher O_2 levels, especially in N_2 diluent***
  - ✓ ***higher volatile flame temperature***
  - ✓ ***higher char combustion temperature***
  - ✓ ***CO_2 effect may reflect thermal NOx and/or lower combustion T***

NOx Measurements: low reburn

Black Thunder coal



Same trends as for Pittsburgh coal, with slightly higher NOx production

Normalization of NOx data

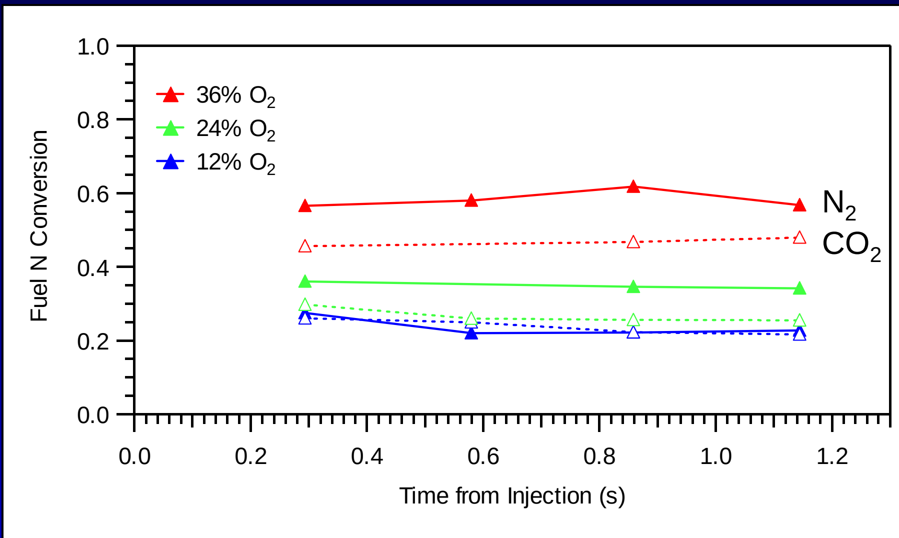
- To compare NOx production for different fuels and fuel injection rates, need to convert measured NOx to "Fuel Nitrogen Conversion"
  - i.e., fraction of N in fuel that is converted to NOx

$$\text{Conversion} = \frac{[\text{NOx}] \cdot \dot{V}(P/RT)}{Y_{N,fuel} \cdot \dot{M}_{fuel} / MW_N}$$

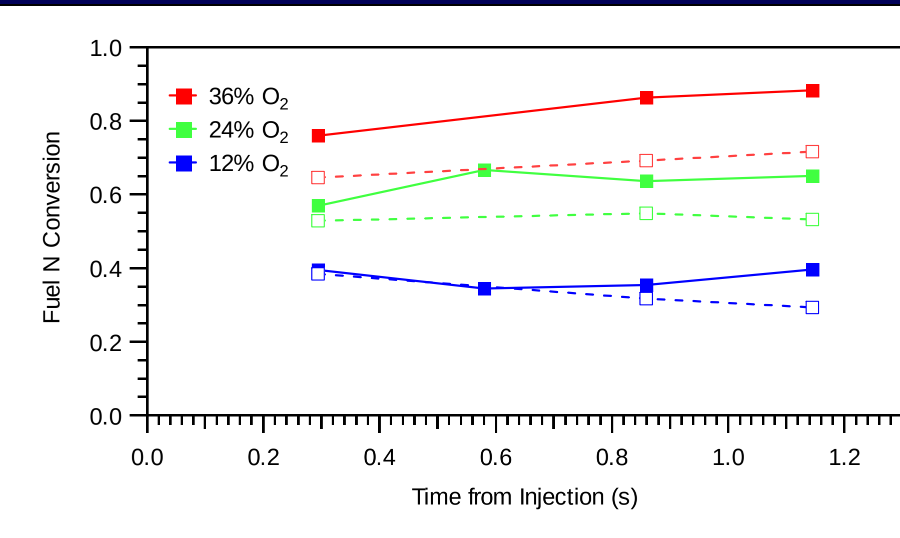
- Has literal meaning for CO_2 diluent with low background NO
- Broader interpretation must be considered for cases of N_2 diluent and/or substantial background NO
  (other sources and sinks of NO)

Fuel N Conversion: low reburn

Pittsburgh coal



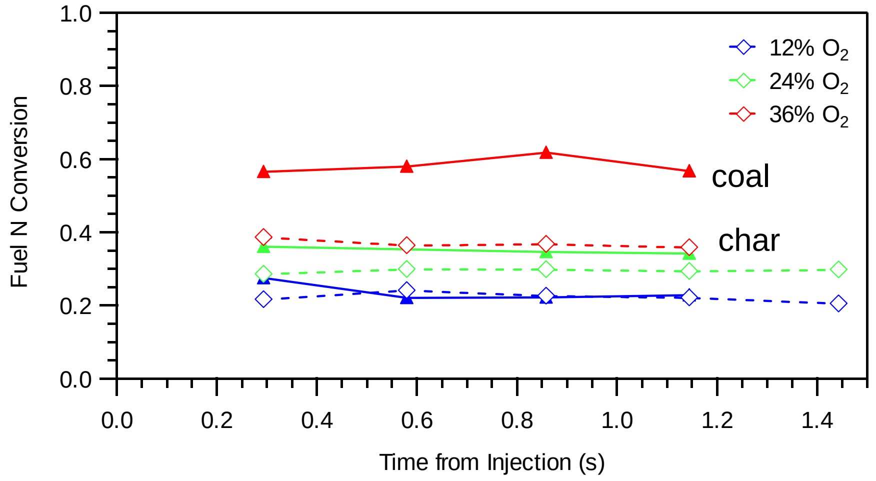
Black Thunder coal



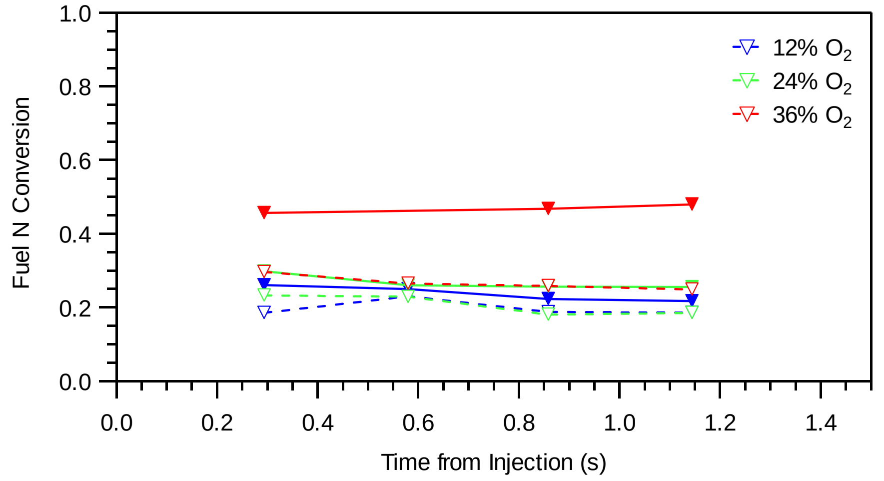
- ***Trends with O_2 still apparent, but differences reduced in relative magnitude***
- ***Black Thunder has substantially higher fuel-N conversion to NOx***
  - ✓ ***higher volatile content***
  - ✓ ***higher char combustion temperature***
  - ✓ ***lower fuel-N content***

Fuel N Conversion: low reburn

Pittsburgh coal vs. char in N_2



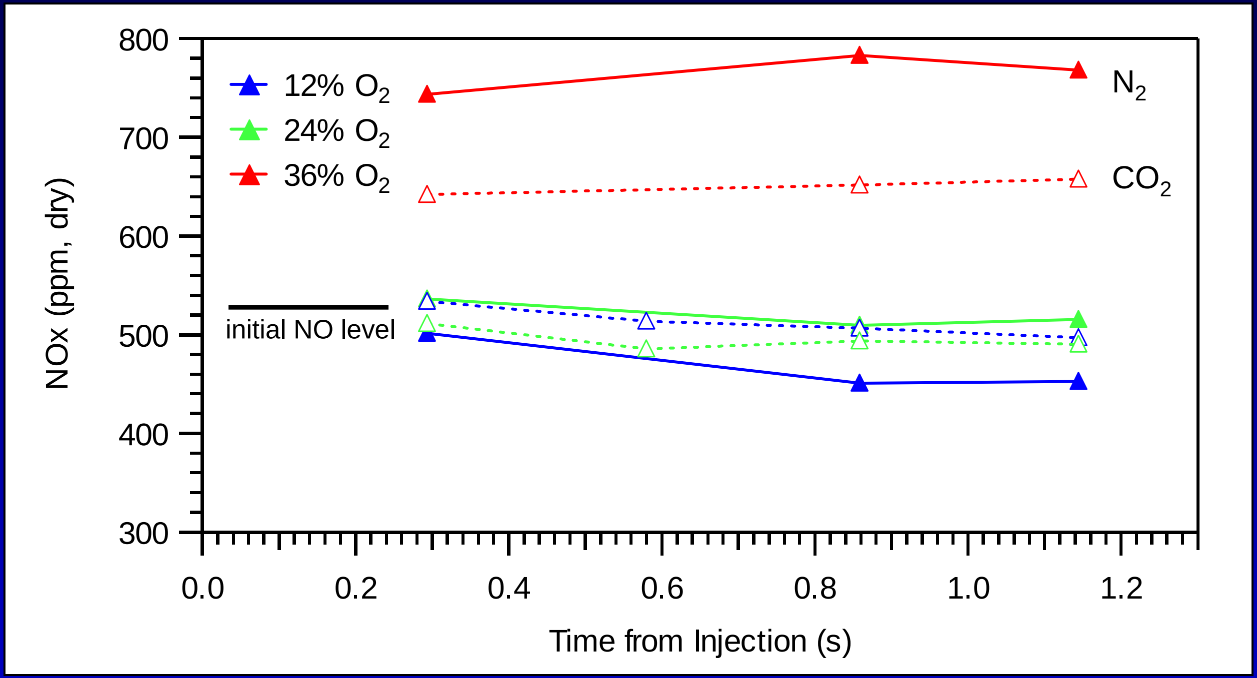
Pittsburgh coal vs. char in CO_2



- ***Volatile-N preferentially produces NOx at elevated oxygen levels***
  - ✓ ***higher volatile flame temperature***
- ***Char-N produces more NOx at elevated oxygen levels (esp. in N_2)***
  - ✓ ***higher char comb. temperature with more O_2, N_2***

NOx Measurements: high reburn

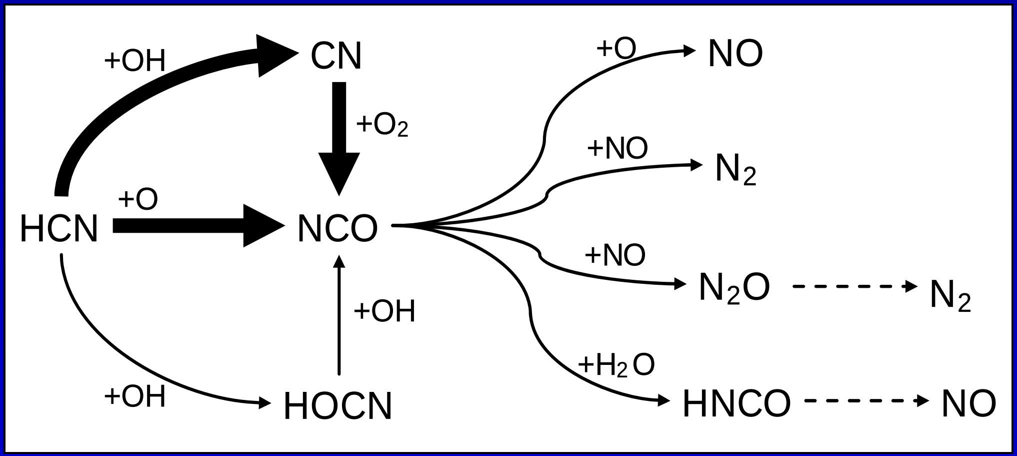
Pittsburgh coal



- ***Overall slight net NOx reduction at 12% and 24% O_2 (i.e. negative fuel-N conversion) and much lower net NOx production at 36% O_2 (N conversion of 0.30 in N_2 and 0.14 in CO_2, compared to 0.60 and 0.45 for low background NO)***
  - ✓ ***demonstrates importance of NOx reburn***

Effect of Char Combustion Temperature and Background NO on Char-N Conversion

- ***Recently completed joint experimental/modeling project provides convincing evidence for dominant route of N release from pc char as CN compound (here modeled as HCN)***
  (manuscript submitted to Comb. Flame)
- ***HCN is oxidized to NCO***
- ***NCO is either oxidized to NO (favored at high temps), or reacts with NO to from N_2 (favored at low temps and for high background NO levels)***



Conclusions

- Elevated O_2 levels and presence of CO_2 bath gas affect NOx formation during oxy-coal combustion
- Black Thunder subbit coal shows substantially higher fuel-N conversion than Pittsburgh hvbit coal under all conditions
- Both volatile-N and char-N show stronger conversion to NOx with increasing O_2
- Char-N shows stronger conversion in presence of N_2 bath gas
- High background NO experiments show importance of NOx reburn reactions
- Reacting particle/chemical kinetic modeling of experiments is being performed to improve understanding of governing mechanisms

Acknowledgments

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

End of Presentation

Questions?

Evaluation of CO_2 Capturing-Repowring System Based on Oxy-Fuel Combustion for Utilizing Low Pressure Steam

Pyong Sik Pak*, Young Duk Lee** and Kook Young Ahn**

* Osaka University
** Korea Institute of Machinery and Materials

Table of Contents

1. Introduction

Advantages of CO_2-capturing power generation system based on oxy-fuel combustion:

- Application to coal fuel is easy.
- 100% capturing of generated CO_2 is possible.
- No thermal NOx is generated, etc.

Disadvantages considered so far:

- Energy efficiency will be significantly deteriorated.
- Economics will be also greatly deteriorated.

Objective of the study:

To show the following characteristics for a proposed CO_2 capturing-repowering system, where low-pressure steam is utilized.

- Efficiency degradation is negligible.
- CO_2-capturing is a technology having a substantially superior cost-effectiveness.

2. Outline of Proposed CO2 Capturing-Repowring System

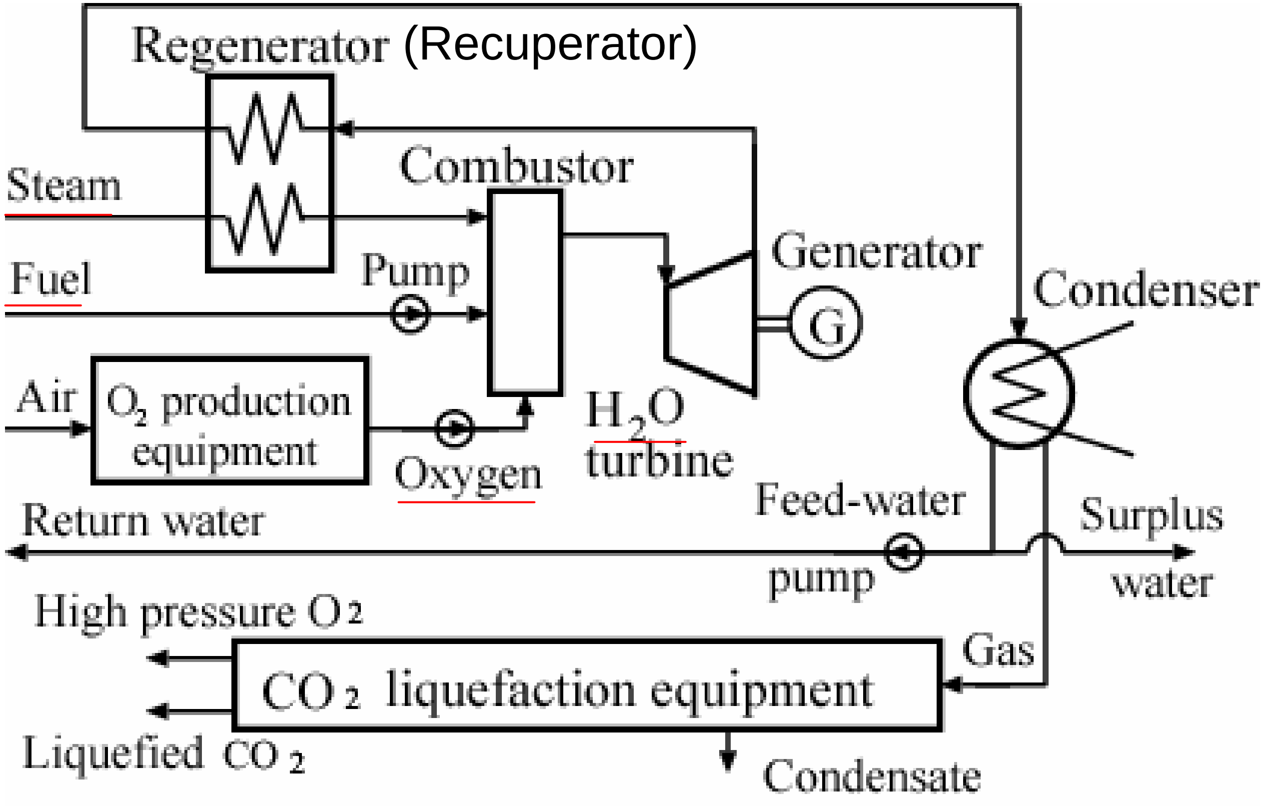


Fig.1 Schematic structure of the proposed CO2 capturing-repowering system based on oxy-fuel combustion (Proposed system).

3. Fundamental Characteristics of the Proposed System

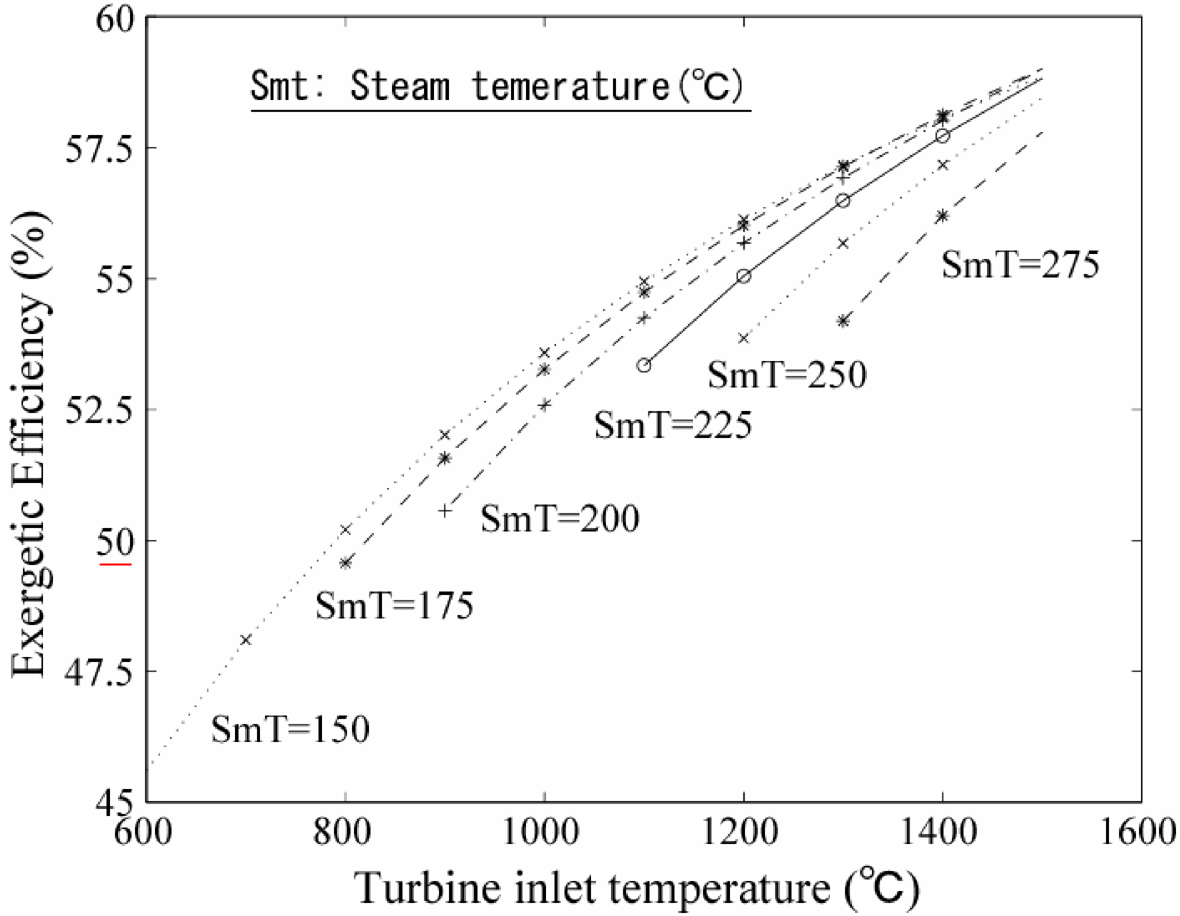


Fig.2 Estimated fundamental characteristics of the proposed system.

The definition of exergetic efficiency:

exergetic efficiency = exergy of the net generated electric power / (exergy of steam + exergy of input fuel) (1)

where

the net generated electric power = generated power
- oxygen production and compression power
- compression power of captured CO_2 to the atmospheric pressure
- miscellaneous power (2)

The power required for liquefaction of the captured CO_2 is discussed in the following chapter.

4. Estimation of Economics and CO_2-Reduction Characteristics

4.1 Premises

- The low-pressure steam from a steam turbine system of an advanced combined-cycle power plant (CCPS) was assumed to be utilized.
- Economic evaluation was assumed to be performed based on unit cost of power (yen/kWh), annual gross profit (yen/year), and depreciation year of the capital.
- CO_2-reduction effect was assumed to be determined by comparing CO_2 amount emitted from the power plant with efficiency of 50% (LHV base) whose electric energy output is same as the proposed system.

In evaluating the characteristics, a steam turbine system, that uses the same low-pressure steam, has been hypothetically introduced and its characteristics are also evaluated, so that both the obtained results are easily compared each other.

The hypothetical steam turbine system is referred to as the reference system in the following.

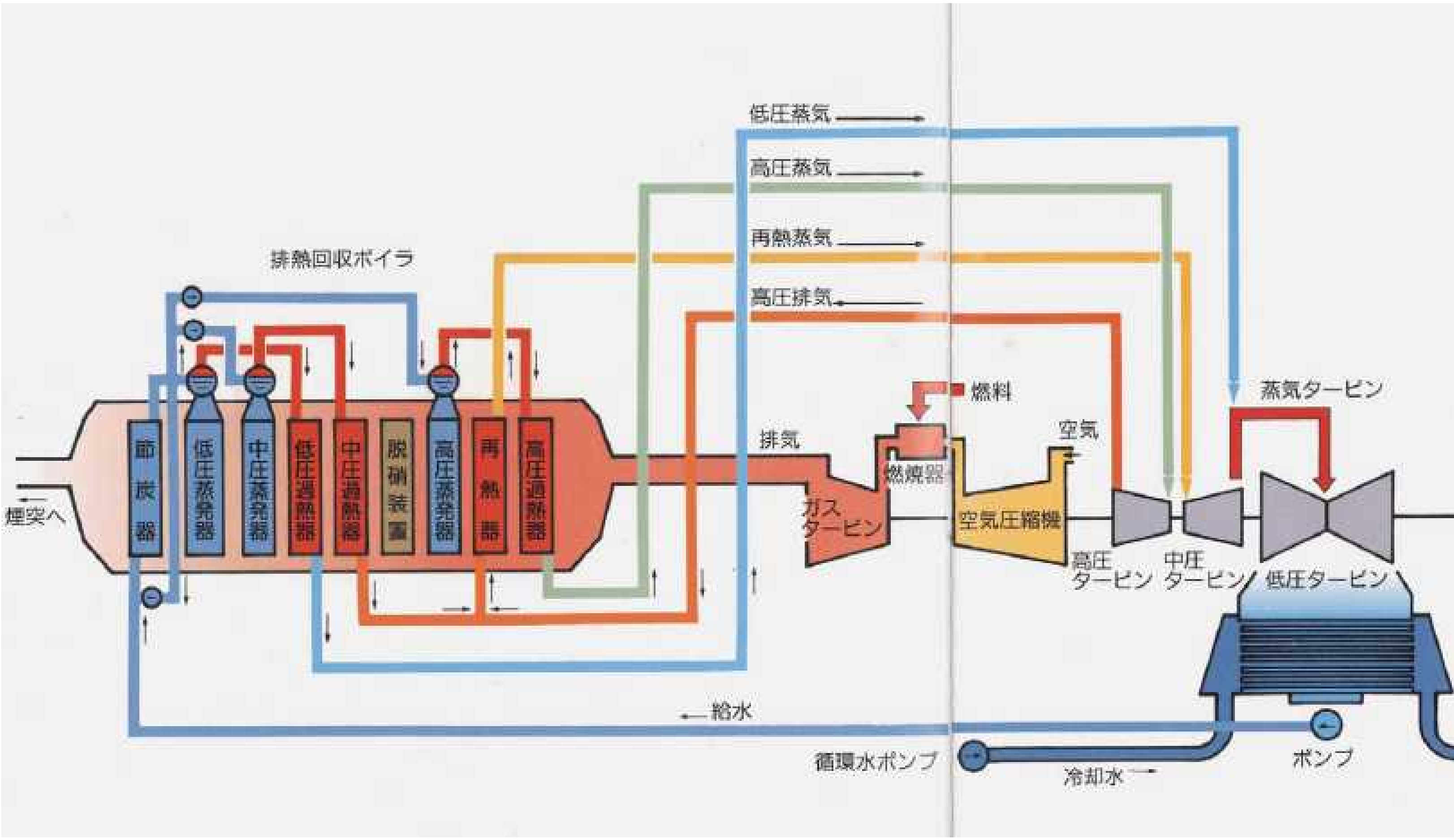
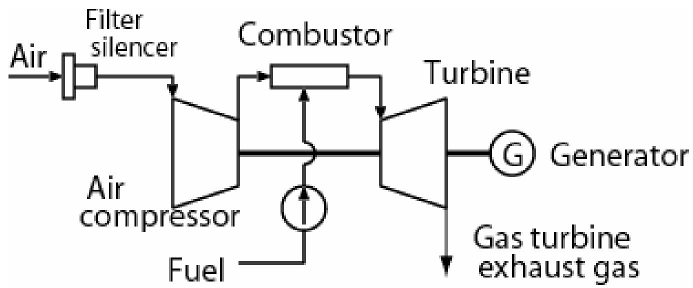
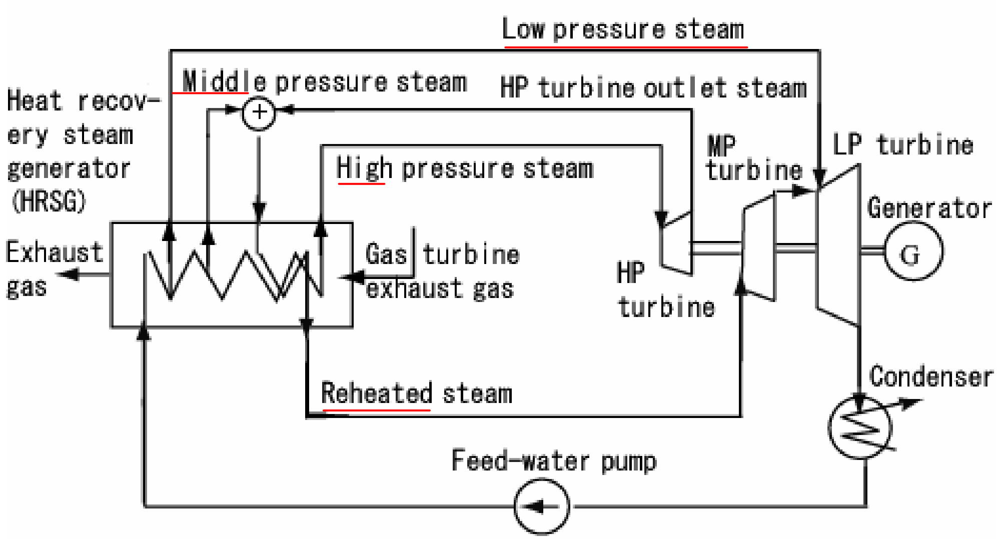


Fig. 3 Schematic structure of the combined-cycle power plant (CCPS) adopted as an conventional thermal power plant

(Kawagoe #3&4 power plants of Chubu Electric Power Co., Japan)



(a) Gas turbine power generation system consisting topping-cycle



(b) Steam turbine power generation system consisting bottoming-cycle

Fig. 3 Schematic structure of the combined-cycle power plant (CCPS) adopted as an conventional thermal power plant

Table 1 Major exogenous variables and parameters used for estimating systems' characteristics.

(a) Exogenous variables

Item	Combined system	Proposed system
Gas turbine		
Power output	200 MW	–
Inlet temperature	1250 deg C	–
Turbine inlet pressure	1.47 MPa	–
Fuel	CH_4	–
Steam turbine		
Pressure of high, middle	9.41, 2.26 and 0.25 MPa	–
and low pressure steam	(96, 23 and 2.5 kg/cm^2)	–
Pressure of reheated steam	2.26 MPa (23 kg/cm^2)	–
Condenser outlet pressure	4.90 kPa (0.05 kg/cm^2)	–
Dryness of turbine outlet steam	higher than 90%	–
H_2O turbine		
Turbine inlet temperature	–	1250 deg C
Condenser outlet temperature	–	32.55 deg C
Condenser outlet pressure	–	9.81 kPa

Table 1 Major exogenous variables and parameters used for estimating systems' characteristics (Continued).

(b) Exogenous parameters

Item	CCPS	Proposed system
Adiabatic efficiency:		
Air compressor	89 %	–
Gas turbine	93 %	–
Steam turbine	90 %	–
H_2O turbine	–	90 %
CO_2 compressor	–	80 %
Heat recovery steam generator (HRSG):		
Terminal temperature difference	60 deg C	–
Pinch point temperature difference	15 deg C	–
Regenerator:		
Temperature efficiency	–	80%
Heating and heated side pressure loss rate	–	5%
Generator efficiency	99 %	99 %
Miscellaneous power consumption rate	3 %	3 %
Unit oxygen production power	–	237.9 kWh/t-O_2
Oxygen excess rate	–	1.01

Table 2 Values assumed for economic evaluation.

Unit cost of power generation facility	50×10^3 yen/kW
Unit cost of oxygen production facility	82×10^6 yen/t-O_2/h
Unit cost of CO_2 liquefaction facility	310×10^6 yen/t-C/h
Life time of the facilities	15 y
Rate of facility maintenance cost	5 %/y
Rate of capital	5 %/y
Unit cost of fuel	0.4 yen/MJ
Steam cost	0.444 yen/MJ
System operation rate	66.667 %
Man-power cost	80×10^6 yen/y
Average power selling cost	12 yen/kWh

4.2 Evaluation Results

Table 3 Estimated power generation characteristics of the CCPS.

Item	Estimated value
Gas turbine	
Generator power output	200 MW
Turbine outlet gas temperature and flow rate	598 deg C, 1649 t/h
Steam turbine	
Temperature and flow rate of high pressure steam	538 deg C, 195 t/h
High pressure turbine outlet steam temperature	332 deg C
Temperature and flow rate of middle pressure steam	302 deg C, 32.0 t/h
Temperature and flow rate of reheated steam	538 deg C, 227 t/h
Temperature and flow rate of HRSG outlet LP* steam	231 deg C, 30.3 t/h
Temperature and flow rate of mixed LP steam	246 deg C, 258 t/h
Pressure of LP steam	0.245 MPa
Generated power	96.0 MW
(High, middle and LP turbine)	(20.9, 36.4, 38.8)
LP turbine net generated power	37.6 MW
Combined system total	
Fuel consumption	1789 GJ/h
Generator and net generated power	296, 278 MW
Net power generation efficiency (Enthalpy-base)	56.0 %
Exergetic efficiency	56.3 %

Table 4 Estimated power generation characteristics of the proposed system when turbine inlet temperature is 1250 deg C.

Item	Estimated value	
Utilized steam:		
Temperature	246 deg C	
Pressure	0.245 MPa	
Flow rate	258 t/h	
Fuel consumption	608 GJ/h	
Generated power	145 MW	cf 38.8 (3.7 times)
Fuel-base efficiency (Enthalpy-base)	85.6 %	
Oxygen production and compression power	13.1 MW	
CO_2 liquefaction power	3.98 MW	
Inhouse power total	28.5 MW	
Inhouse power rate	19.7 %	
Net generated power	116 MW	cf 37.6 (3.1 times)
Net generated power increase rate	209 %	
Amount of captured CO_2	33.3 t-CO_2/h	
Exergetic efficiency	55.0 %	-1.25% down
Exergetic efficiency (after CO_2 liquefaction)	53.2 %	
Repowring efficiency	48.9 %	
Repowring efficiency (after CO_2 liquefaction)	46.5 %	

Table 5 Estimated results of economics and CO_2-reduction effects.

(a) Steam turbine power generation system （Reference system）

Item	Estimated value
Generated power	38.8 MW
Net generated power	37.6 MW
Steam-base power generation efficiency	20.0 % (Enthalpy-base)
Exergetic efficiency	77.0 %
Depreciation cost	0.187×10^9 yen
Maintenance cost	97.0×10^6 yen
Steam cost	1.98×10^9 yen
Annual power generation cost	2.35×10^9 yen
Unit cost of power	10.7 yen/kWh
Annual power selling income	2.63×10^9 yen
Annual gross profit	0.288×10^9 yen
Depreciation year	4.69 year
Amount of CO_2 reduction	86.6 kt-CO_2/y

Table 5 Estimated results of economics and CO2-reduction effects Continued).

(b) Proposed system

Item	Estimated value
Cost of oxygen production facility	4.02×10^9 yen
Cost of CO_2 liquefaction equipment	2.82×10^9 yen
Total facility cost	14.1×10^9 yen
Cost rate of oxygen production facility	28.5 %
Cost rate of CO_2 liquefaction equipment	20.1 %
Depreciation cost	1.36×10^9 yen
Maintenance cost	703×10^6 yen
Steam cost	1.98×10^9 yen
Fuel cost	1.42×10^9 yen
Annual power generation cost	5.54×10^9 yen
Unit cost of power	8.17 yen/kWh
Annual power selling income	8.14×10^9 yen
Annual gross profit	2.60×10^9 yen
Depreciation year	4.01 year
Amount of CO_2 reduction	268 kt-CO_2/y
Amount of net CO_2 reduction	181 kt-CO_2/y
Profit of CO_2 reduction	12.8×10^3yen/t-CO_2

Table 6 Comparison of estimated characteristics of the proposed and reference systems.

Item	Proposed system	Reference system	
Depreciation cost (10^9 yen)	1.36	0.187	(7.3 times)
Maintenance cost (10^6 yen)	703	97.0	
Steam cost (10^9 yen)	1.98	1.98	
Fuel cost (10^9 yen)	1.42	0	
Annual power generation cost (10^9 yen)	5.54	2.35	(2.4 times)
Unit cost of power (yen/kWh)	8.17	10.7	
Annual power selling income (10^9 yen)	8.14	2.63	
Annual gross profit (10^9 yen)	2.60	0.288	(9.0 times)
Depreciation year (year)	4.01	4.69	
Amount of CO_2 reduction (kt-CO_2/y)	268	86.6	(3.1 times)
Amount of net CO_2 reduction (kt-CO_2/y)	181	–	
Profit of CO_2 reduction (10^3yen/t-CO_2)	12.8	–	

5. Conclusion

The thermodynamic characteristics and economics of the proposed CO_2 capturing-repowring system, that utilizes low-pressure steam, were evaluated.

From a case study performed, the following characteristics have been obtained:

- It is possible to generate 2.09 times larger electric power with the exergetic efficiency of 55.0 %, even if all the generated CO2 is captured.
- The estimated exergetic efficiency degradation is only 1.25% compared with that of the original high-efficiency advanced combined cycle power plant.
- The economics of the proposed system have been estimated to be excellent compared with the reference system (conventional steam turbine power plant).
- The net CO_2 reduction effect has been estimated to be 181 kt-CO2/y, and is greater than 2.09 times larger than that of the reference system.
- Reducing CO_2 emission brings about an economical merit, not the cost, and it has been estimated to be 12,800 yen per captured 1 ton of CO_2.

Reference

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7) Pyong Sik Pak: Evaluation of Exergetic Characteristics of CO2-Capturing H2O Turbine Power Generation Systems Based on Oxygen Combustion Method, Energy and Resources, Vol.25, No4. pp.272/2782, 2004.7
8) Pyong Sik Pak: Characteristics of CO2-Capturing Systems Based on Oxy-Fuel Combustion and Exergetic Flow Analyses for Improving Efficiency, Journal of the Gas Turbine Society of Japan, Vol.34, No.5, pp.356/362, 2006.9
9) T. Kosugi and P. S. Pak: Object-oriented simulation system for evaluating characteristics of various CO2-capturing thermal power generation systems, JSST International Conference on Modeling, Control and Computation in Simulation, pp.294/299, Tokyo, Japan (Oct. 2000).

Efficiency Increase of the Oxyfuel Process by Waste Heat Recovery Considering the Effects of Flue Gas Treatment

Mathias Klostermann

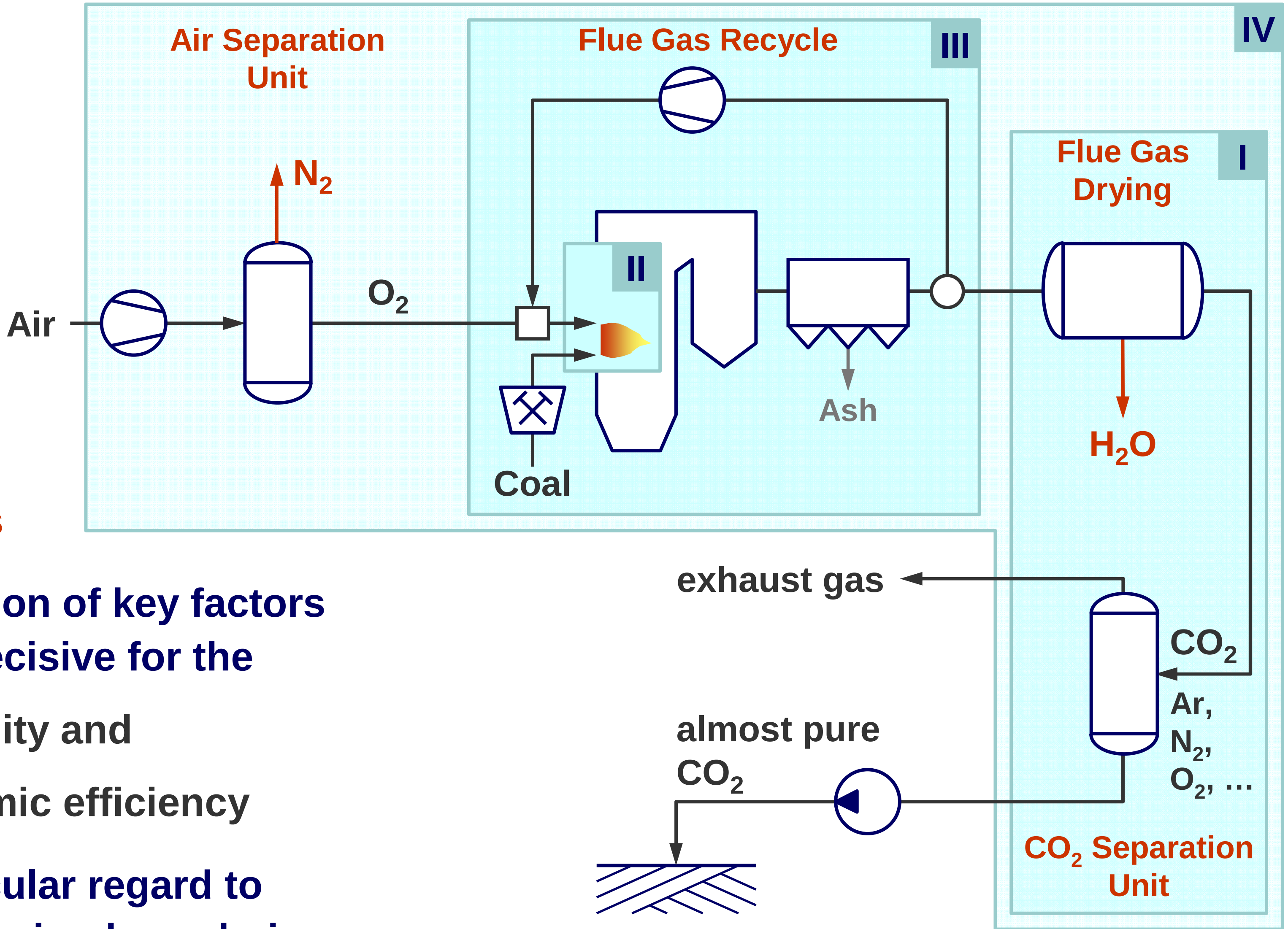
Institute of Energy Systems

Prof A Kather
C Hermsdorf
M Klostermann
K Mieske

TUHH
Technische Universität Hamburg-Harburg

IEAGHG International Oxy-Combustion Network - 3rd Workshop,

5th and 6th March 2008, Yokohama Japan



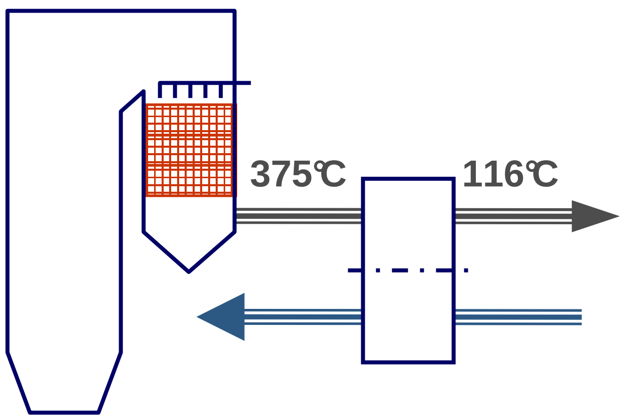
Objectives

Identification of key factors that are decisive for the

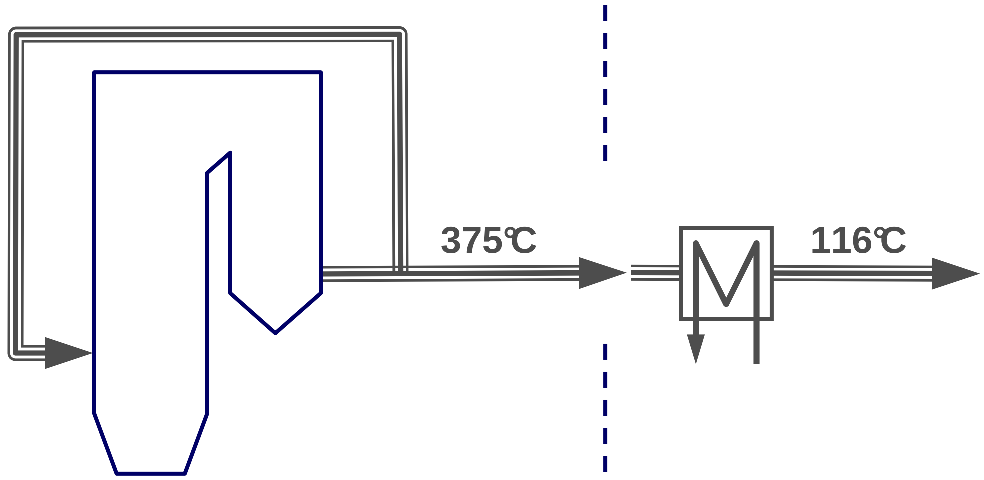
- feasibility and
- economic efficiency

with particular regard to realistic design boundaries

Air



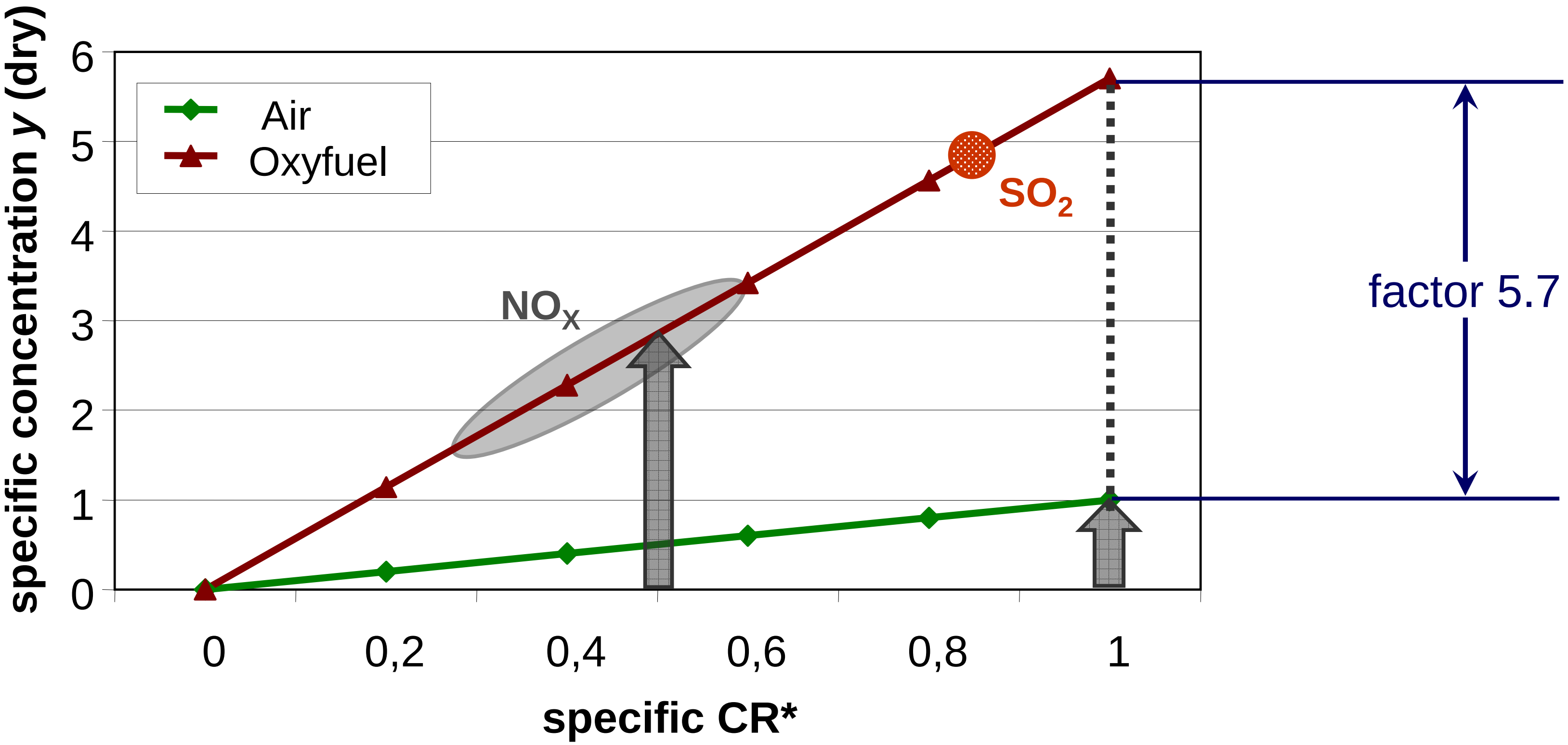
Oxyfuel



$Q_{flue\ gas}$	MW	67.4	MW	60.8	MW	17.4
$m_{flue\ gas}$	kg/s	541	kg/s	149	kg/s	145
η_{boiler}	%	94.5	%	95.0	%	98.5

- **Significant increase of the boiler efficiency (approx. 4 %-pts) results in an overall efficiency increase potential of approx. 1.4 %-pts.**

⇨ **What is the potential under realistic boundary conditions?**

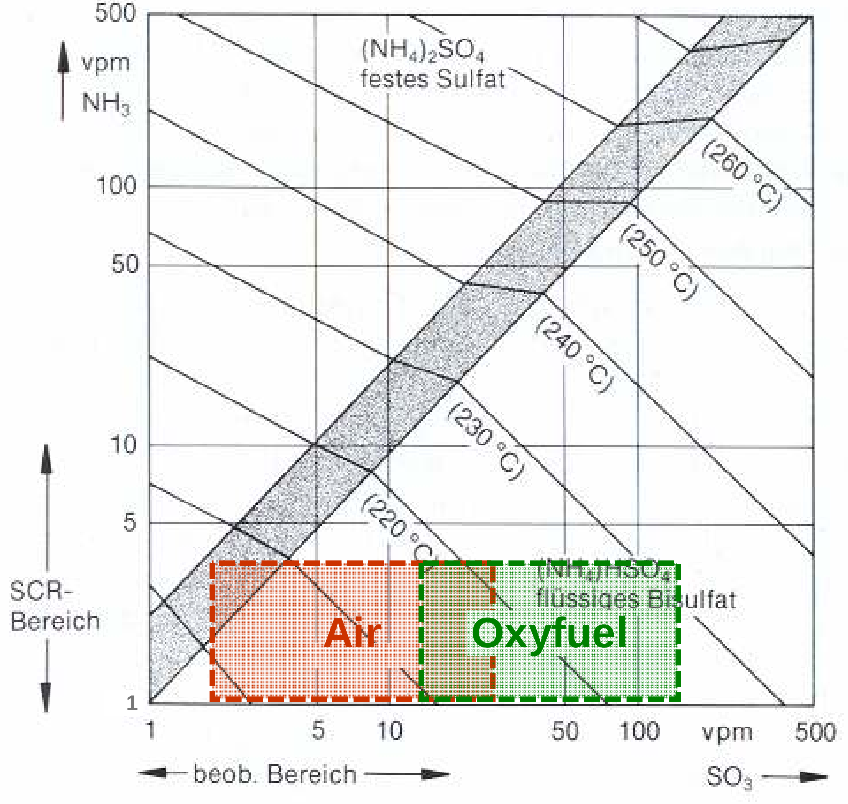


Causes:

- **lower specific flue gas mass flow**
- **increase of flue gas density**
- **higher water content in flue gas**
- **significant inhibition of NO_X formation**
- **SO_2 conversion rate (CR) similar to air case**

NO_x

- approx. 1200 mg/m³ @stp dry
  - Reduction prior to CO_2-condensation seems to be necessary
- High-dust SCR is a state-of-the-art technology
  - approx. 90 % NO_x conversion
  - NH_3 slip approx. 1.5 ppm_v
  - partial conversion of SO_2 ⇨ SO_3
  - formation of sticky and corrosive ammonium bisulfate, risk of scaling on downstream heat exchangers



Formation temperatures of ammonium bisulfate and ammonium sulfate [Thyssen Engineering GmbH 1985]

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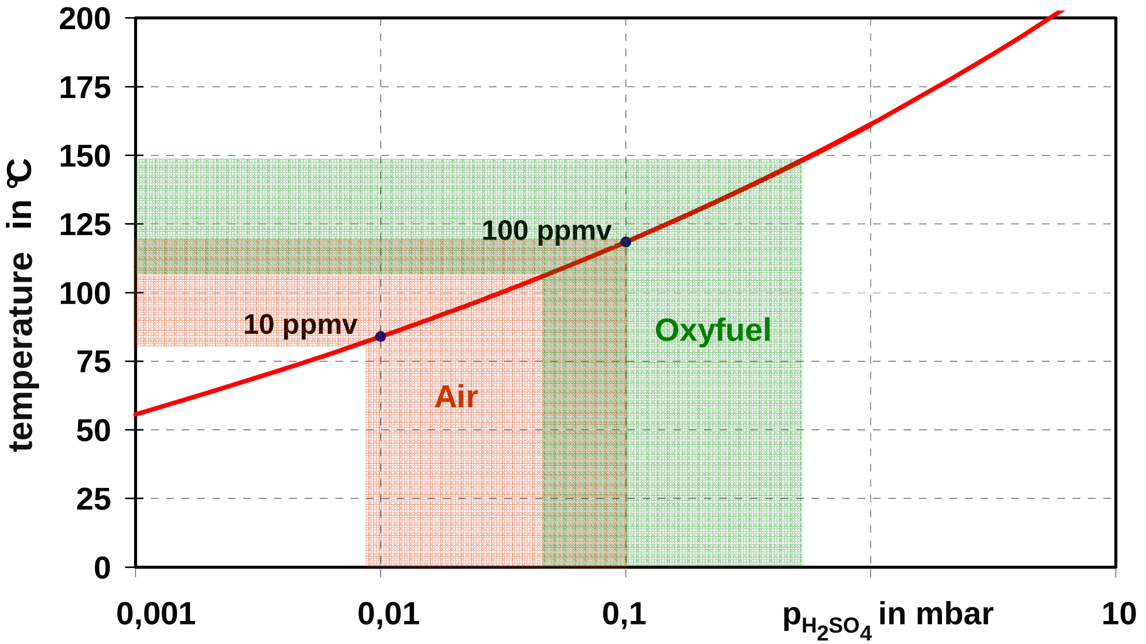
SO_x

- SO_3 fraction of SO_x between 1 and 5 %
- SO_3 formation promoted by higher concentrations of oxygen and water
- higher concentration due to missing nitrogen

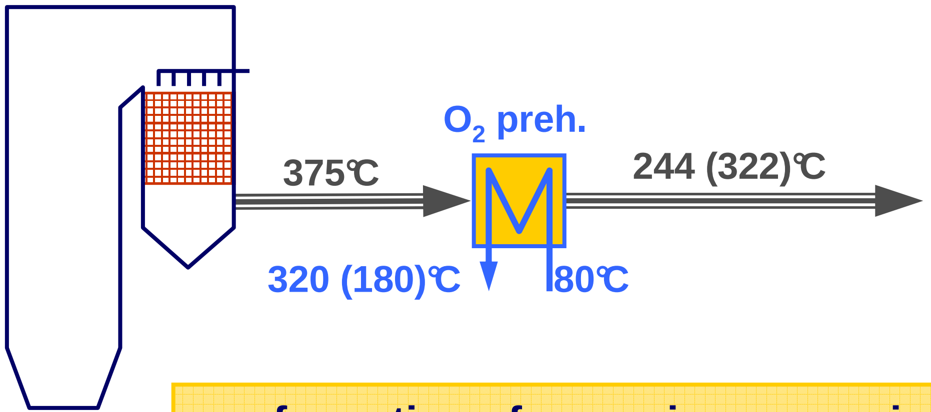
⇨ +20....40 K higher acid dew point temperature of the flue gas

vapour pressure curve of sulphuric acid



- **Oxygen preheating** (with a tubular heat exchanger)
  - \+ maximum efficiency increase, identical in function as air preheating
  - \- high technical requirements of oxygen handling at elevated temperatures
  - \- low heat transfer coefficient (gas-gas) ⇨ large heating surface
- **Boiler feed water preheating**
  - \+ simple waste heat recovery process (similar to an economizer)
  - \+ low risks in case of damage
  - \- lower efficiency increase (compared with oxygen preheating) particularly for low pressure condensate preheating
  - \- complexity of controlling the bypass
- **Additional power cycle** (e.g. ORC)
  - \+ less complex design
  - \+ direct coupling with power turbines
  - \- lower efficiency increase compared with oxygen preheating

Oxygen preheating

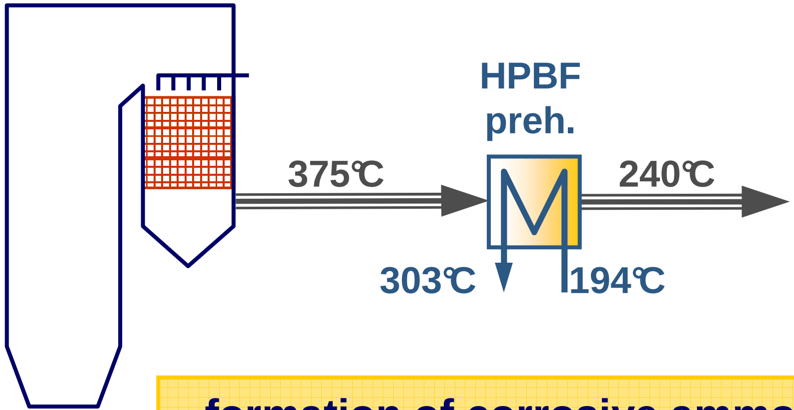


T_{oxygen}	℃	(180)	320
Q_{oxygen}	MW	9.1	21.9
$\Delta\ \eta_{net}$	%Pts	+0.6	+1.15

formation of corrosive ammonium bisulfate from NH_3 and SO_3

- **maximum efficiency increase**
- **Risk of damage as well as firmly bonded deposits at the oxygen preheater in the presence of an upstream high-dust SCR !**

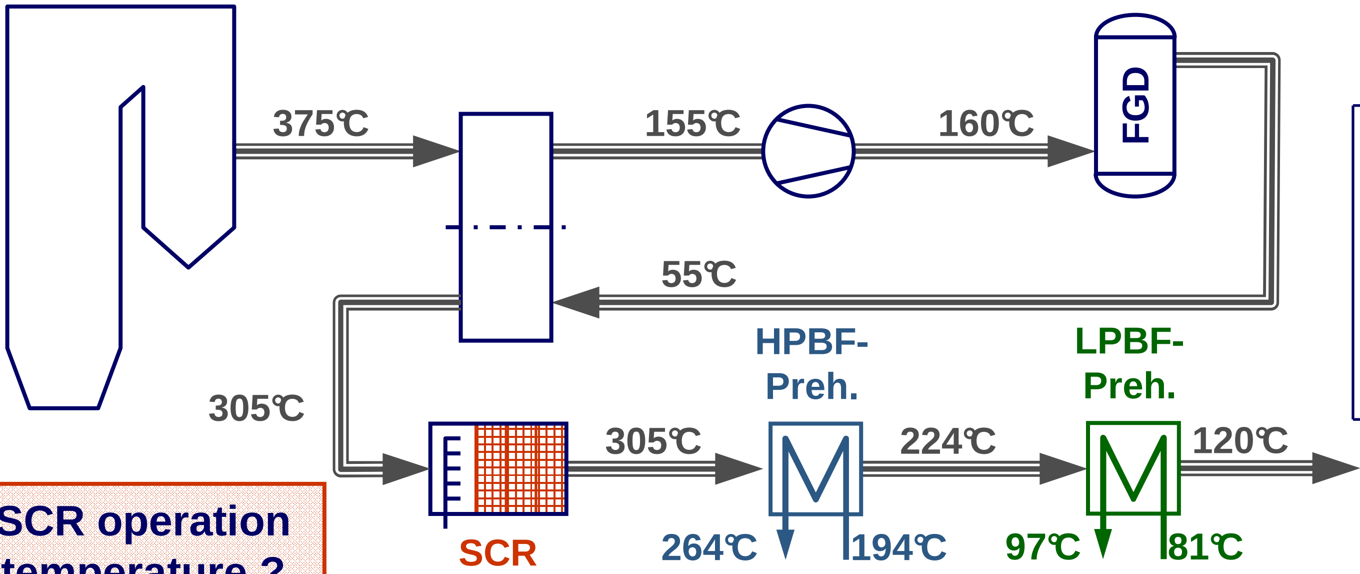
Boiler feed water preheating



Q_{HPBF}	MW	23.6	23.6
Q_{LPBF}	MW	-	18.3
$\Delta\eta_{net}$	%pts	1.05	+1.25

formation of corrosive ammonium bisulfate from NH3 and SO3

low temperature corrosion



Q_{HPBF}	MW	12.7
Q_{LPBF}	MW	15.5
$\Delta\eta_{net}$	%pts	0.85

SCR operation temperature ?

Conclusions

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- **Waste heat recovery from oxyfuel flue gas increases the overall net-efficiency significantly.**
- **Operation of a high dust SCR could cause problems with scaling and corrosion by ammonium bisulfate.**
- **Higher concentrations of SO_x increase the acid dew point temperature of the flue gas.**
  - higher risk of corrosion in case of low flue gas and water temperatures
- **Boiler feed water heating is the most promising option.**
  - high efficiency increase
  - limited risk of corrosion

Thank you

for your attention!

3rd Workshop

IEAGHG International Oxy-Combustion Network
Yokohama, Japan

5th and 6th March 2008

Purification of Oxyfuel-Derived CO_2

Vince White
Air Products PLC, UK
5th March 2008

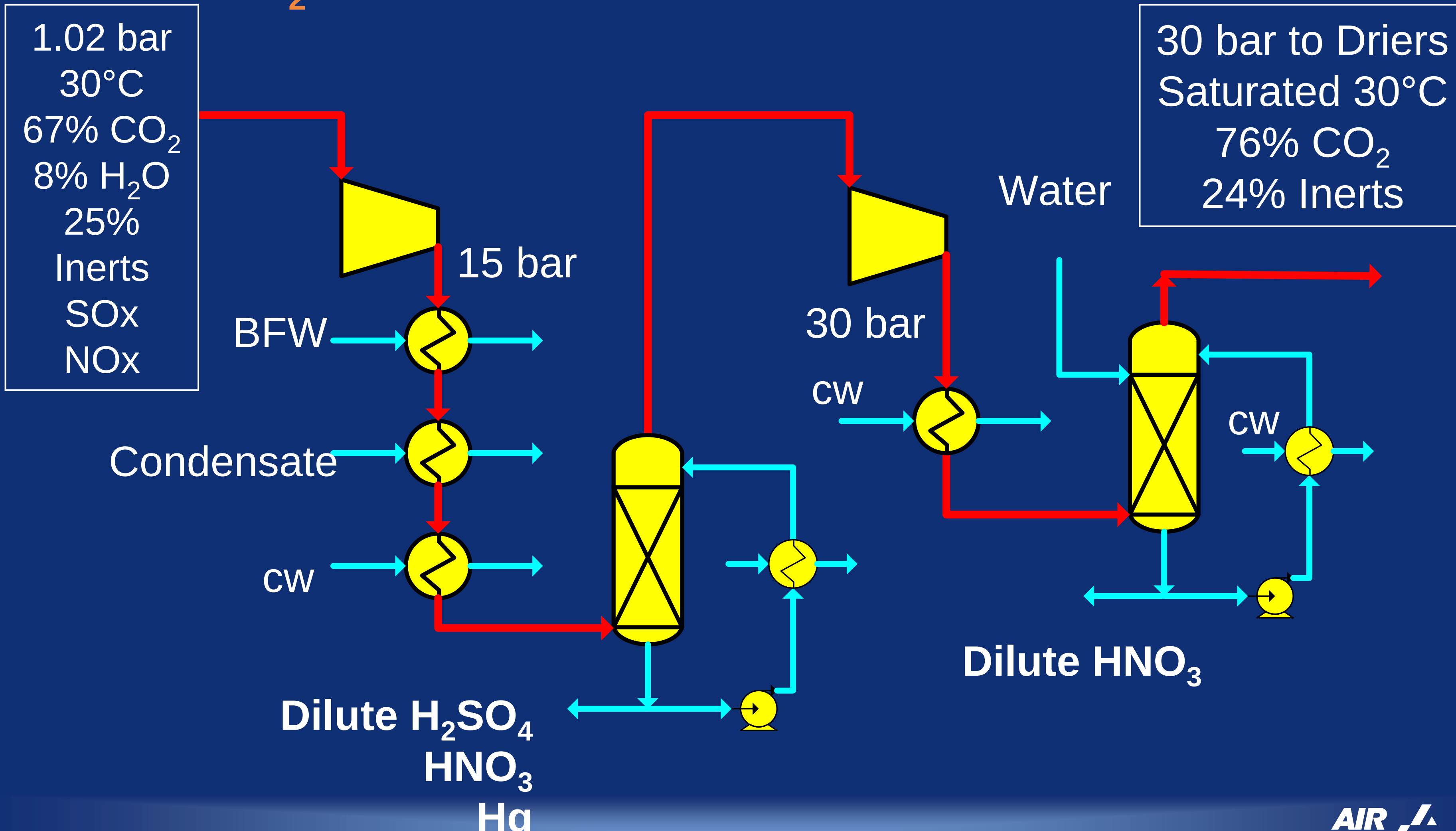
AIR PRODUCTS

Purification of Oxyfuel-Derived CO_2: Outline

- **Compression to 30 bar with integrated SOx/NOx/Hg removal**
- **Integrated purification and compression**
  - **Low purity, bulk inerts removal**
  - **High purity, Oxygen removal**
  - **Membrane for high CO_2 recovery**
- **BERR 404 Project: Oxyfuel Fundamentals**
- **Development plan**

Air Products' CO_2 Compression and Purification System: Removal of SO_2, NOx and Hg

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



NOx SO_2 Reactions in the CO_2 Compression System

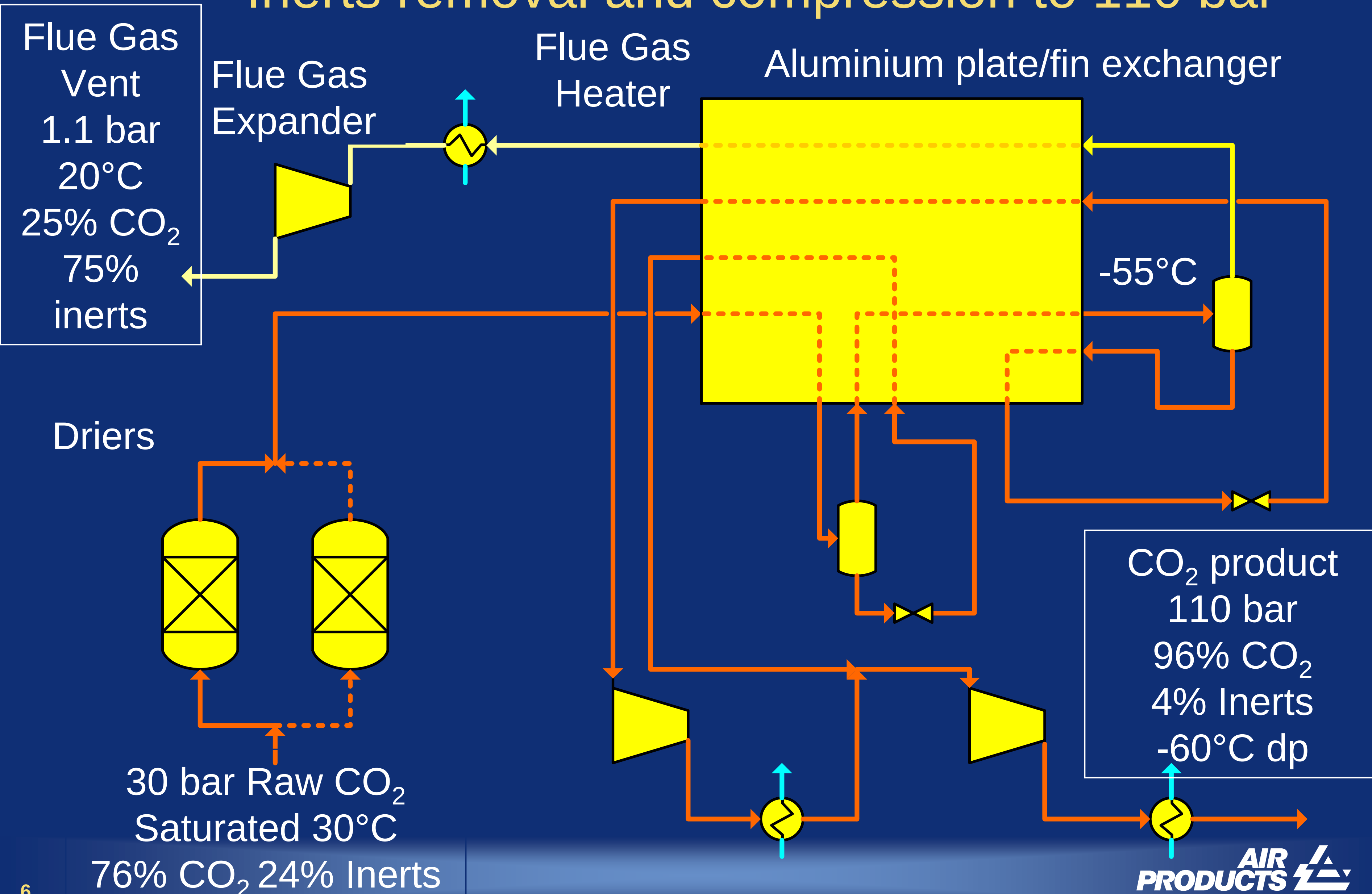
- We realised that SO_2, NOx and Hg can be removed in the CO_2 compression process, in the presence of water and oxygen.
- SO_2 is converted to Sulphuric Acid, NO_2 converted to Nitric Acid:
  - $NO + ½\ O_2 = NO_2$ (1) Slow
  - $2\ NO_2 = N_2O_4$ (2) Fast
  - $2\ NO_2 + H_2O = HNO_2 + HNO_3$ (3) Slow
  - $3\ HNO_2 = HNO_3 + 2\ NO + H_2O$ (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.

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**
- **FGD and DeNOx systems are not required for emissions or CO_2 purity**
  - SOx/NOx removed in compression system
  - Low NOx burners are not required for oxyfuel combustion

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



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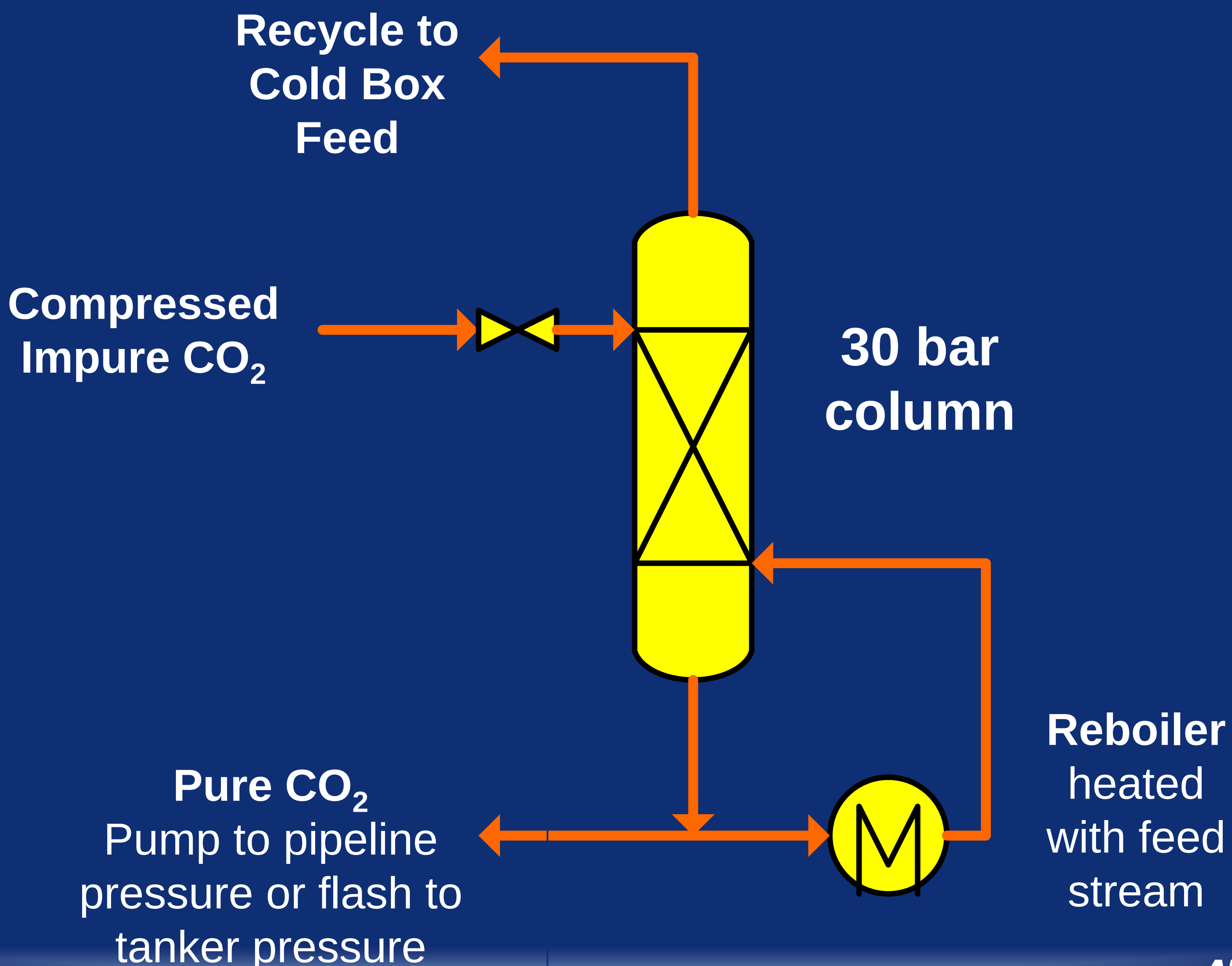
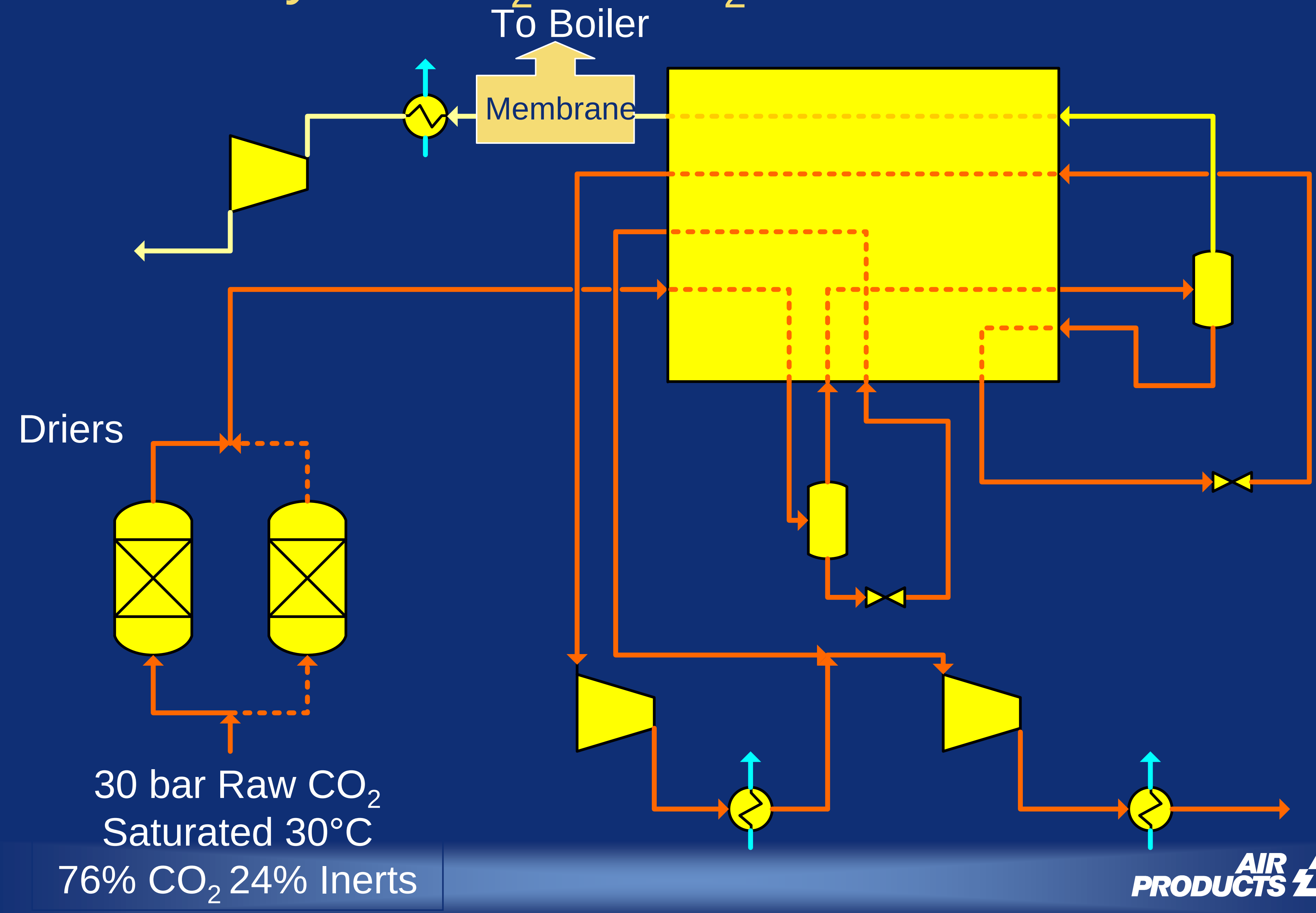
Oxygen removal to ppm O_2 in CO_2



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



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CO_2 Purity and Recovery

- -55°C is as cold as we can make the phase separation
- Impure CO_2 purity depends on pressure: higher pressure gives lower purity CO_2
  - At 30 bar and -55°C, CO_2 purity is 95%
- CO_2 recovery depends on pressure: lower pressure gives lower CO_2 recovery
  - 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%
- Oxygen can be removed to produce EOR-grade CO_2
- No penalty if CO_2 is required as a liquid
- Vent stream is clean, at pressure and rich in CO_2 (~25%) and O_2 (~20%)
  - Polymeric membrane unit – selective for CO_2 and O_2 – in vent stream will recycle CO_2 and O_2 rich permeate stream to boiler.
  - CO_2 Capture increase to >97%
  - ASU size/power reduced ~5%

OxyCoal-UK : Phase 1 – Project Participants

Lead Company
Doosan Babcock Energy Limited

University Participants
Imperial College London
University of Nottingham

Industrial Participants

Air Products plc

BP

E.ON UK Limited
RWE

Sponsors / Sponsor Participants
Scottish and Southern Energy
Scottish Power
EdF Energy
Drax Power Limited
Dong Energy Generation A/S

Government Support
Department of Business, Enterprise and Regulatory Reform

OXYCOAL-UK : Phase 1 : BERR 404 Oxyfuel Fundamentals

- **WP1: Combustion Fundamentals**
- **WP2: Furnace Design & Operation**
- ***WP3: Flue Gas Clean-up / Purification***
- **WP4: Generic Process Issues**

Work Package 3: Objectives

- **Confirmation of CO_2, O_2, H_2O, SO_2, NOx reaction/purification chemistry over range of T & P**
- **Provision of data to enable development of reliable kinetic model**
- **Validation on side stream of pilot test rig and check of Hg removal**

Work Package 3: People

- **Imperial College:**
  - **Sandro Macchietto – Prof of Process Systems Engineering, Dept of Chemical Engineering**
    - **Alex Sturt**
  - **David Chadwick – Prof of Applied Catalysis, Dept of Chemical Engineering**
    - **Laura Torrente Murciano**
  - **Peter Lindstedt – Prof of Thermofluids, Dept of Mechanical Engineering**
    - **Roger Robinson**
- **Doosan Babcock:**
  - **Clive McGhie – Test Rig Manager**

Methodology

- Theoretical study of CO_2, O_2, H_2O, SO_2, NOx reaction/separation mechanism
- Model-based optimal design of experiments for kinetics identification
- Experimental study using simulated feed compositions over range of T & P and residence time
- Laboratory-scale rig consisting of stirred vessel with gas and liquid chemical analysis
- Development and validation of kinetic model
- Installation of small scale apparatus at pilot plant site and testing with realistic flue gas
- Adjustment of design & operating conditions

Completed so far…

- Completed literature review on nitrogen oxides reactions.
- Completed literature review on sulphur dioxide reactions.
- Identified three kinetic models of increasing complexity as basis candidates for further study.
- Constructed stirred autoclave system (Buchi) for initial measurements.
- Reviewed analytics for initial experiments with the batch reactor.
- Initiated design of loop reactor system.

Next Steps…

- Modelling
  - Start develop reaction software models
  - Theoretical predictions from first principles
  - Review data and possible mechanisms for inclusion of Hg

- Experimental
  - Commission batch reactor
  - Conduct initial experiments with CO_2 at simulated levels of SO_3 and NOx removal
  - Complete design of loop reactor
  - Conduct experiments on NRTF flue gas

Doosan Babcock NO_x Reduction Test Facility (NRTF)

- **Heat Input: 160kW**
- **In-Furnace (Primary) NOx Reduction Technologies**
  - **Air Staging, Overfire Air (OFA) injection**
  - **Gas and Coal Reburn**
- **Post-Combustion (Secondary) NOx Reduction Technologies**
  - **Selective Non-Catalytic Reduction (SNCR)**
  - **Selective Catalytic Reduction (SCR)**
- **Electro Static Precipitator (ESP)**
- **Oxyfuel experiments carried out early 90's with Air Products/Babcock Energy**

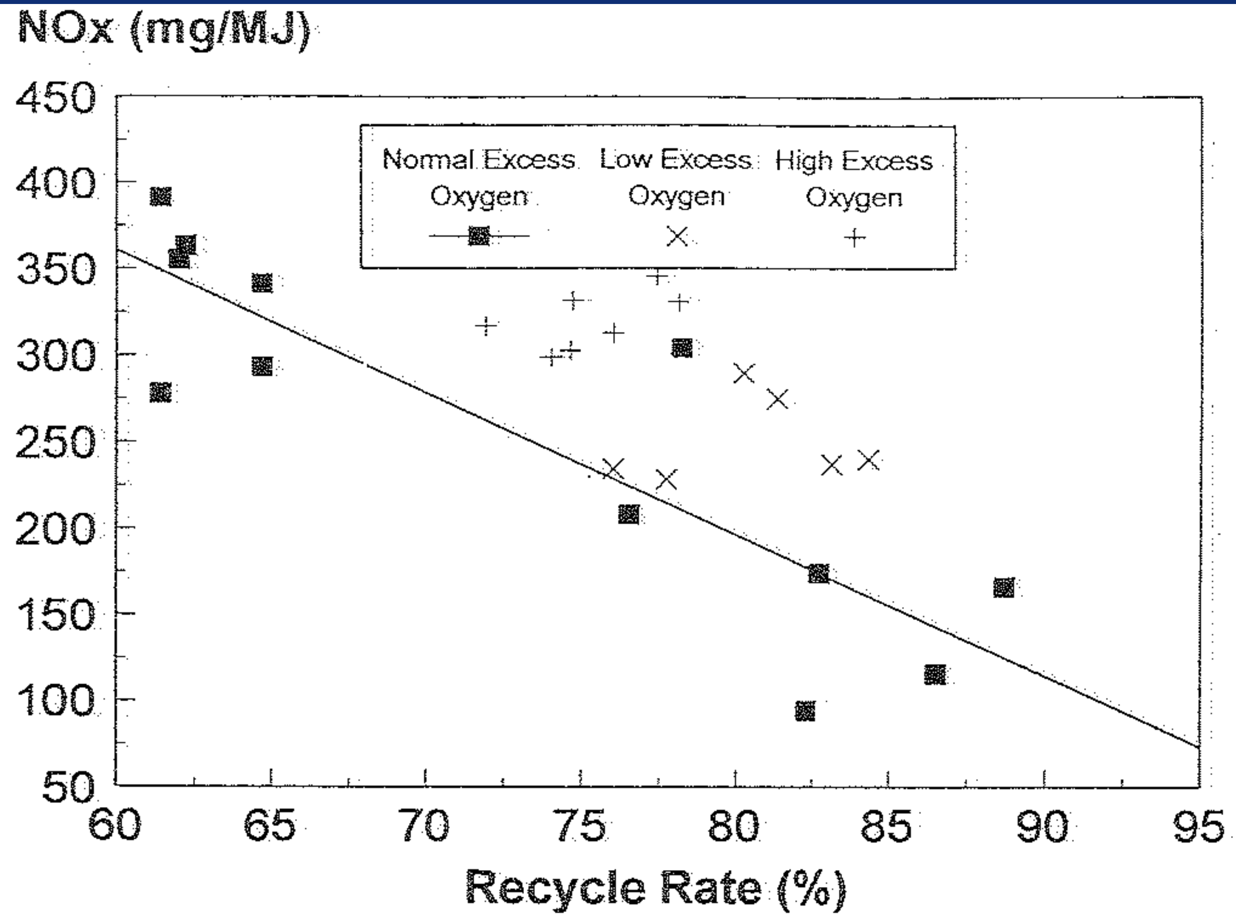
PULVERISED COAL COMBUSTION SYSTEM FOR CO_2 CAPTURE

BABCOCK ENERGY LIMITED
AIR PRODUCTS PLC
UNIVERSITY OF ULSTER
UNIVERSITY OF NAPLES

OCTOBER 1995

Commission of the European Communities
Directorate General XII for
Science, Research and Development

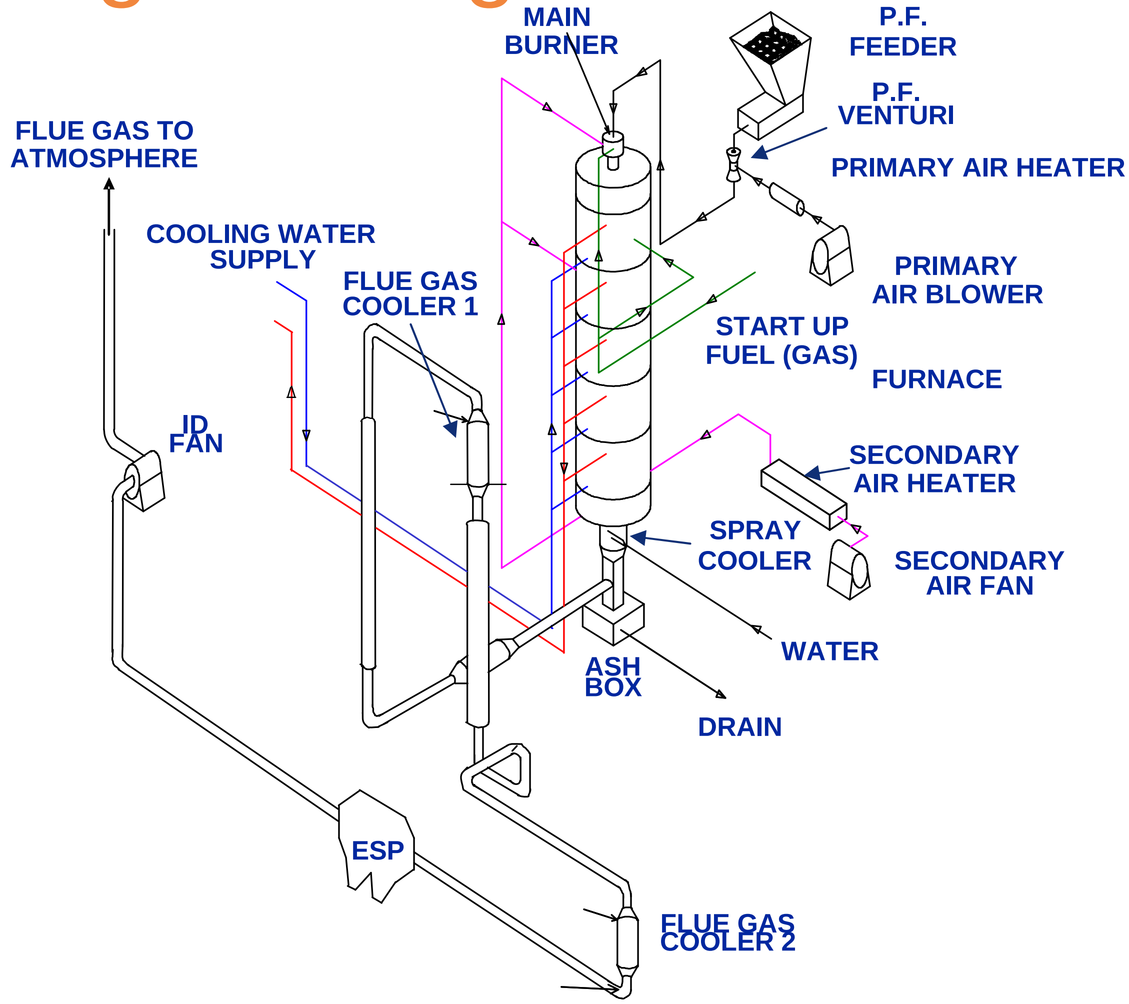
JOULE II Programme
Clean Coal Technology R&D
Contract No. JOU2-CT92-0062



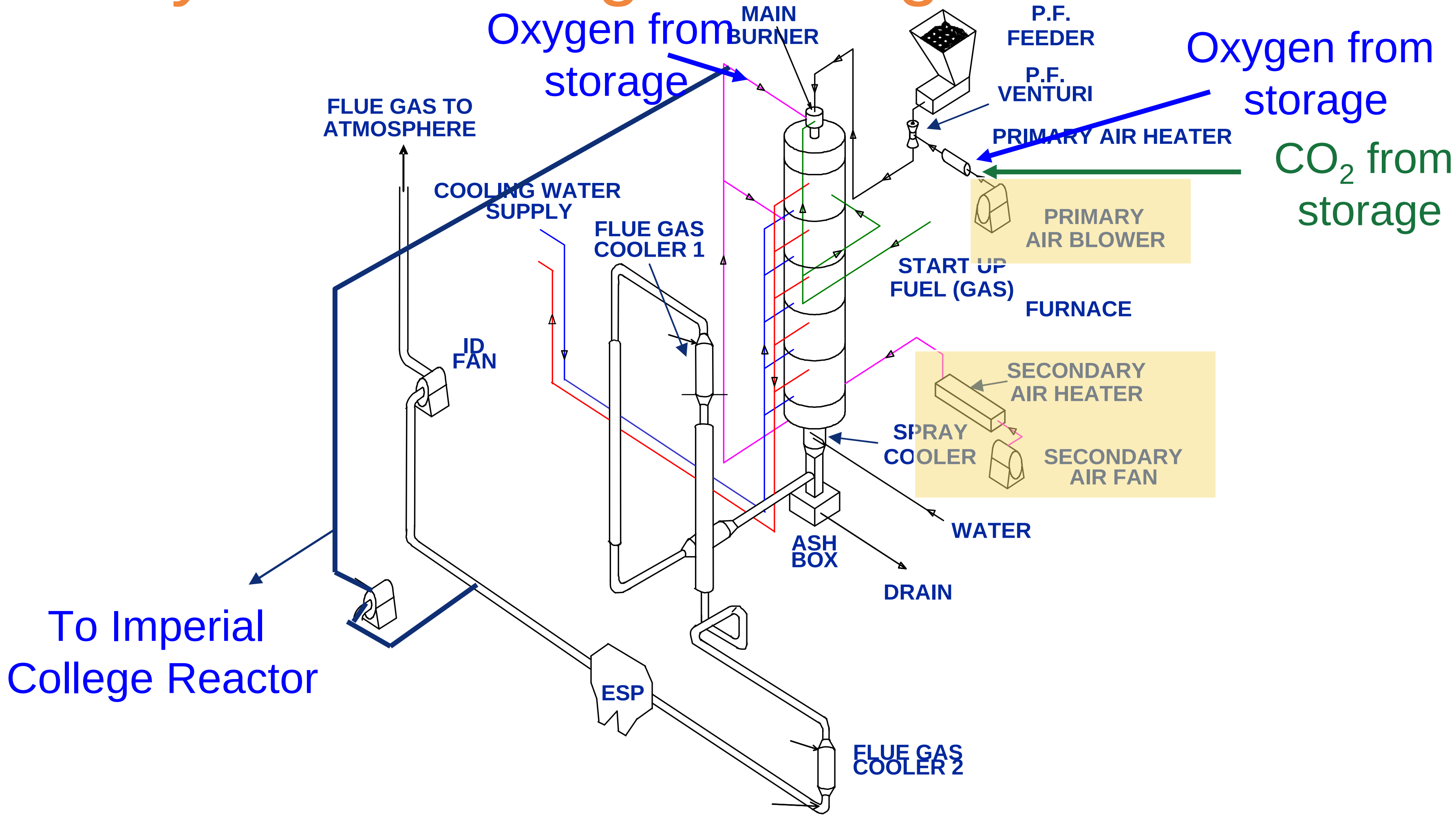
Doosan Babcock Energy

AIR PRODUCTS

Schematic Diagram of NRTF – Air Firing Configuration



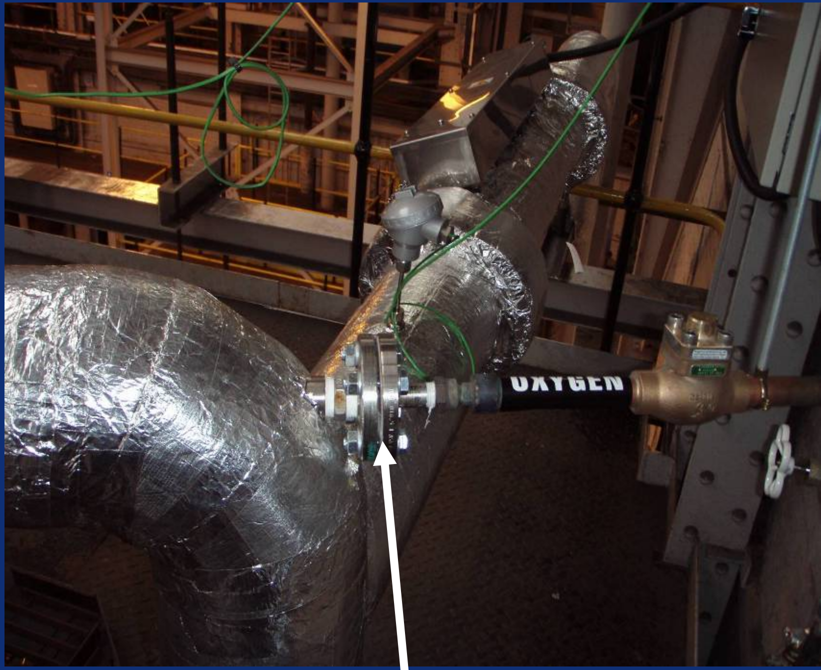
Schematic Diagram of NRTF – Oxyfuel Firing Configuration



Oxyfuel Installation

Flue Gas Recycle Fan

Flue Gas Recycle



Oxygen Injection Into Secondary

Plan for Development of Air Products' Oxyfuel CO_2 Purification and Compression System

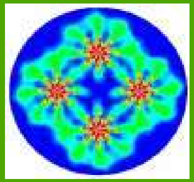
- Step 1: Lab results from Imperial College
- Step 2: Testing with real flue gas from Doosan Babcock's NRTF
  - Commission in March, run experiments April to June
- Step 3: Update model of process
- Step 4: 1 MW equivalent pilot plant in 2009
- Step 5: 300 MW demonstration plant?

AIR PRODUCTS

Thank you

tell me more

www.airproducts.com

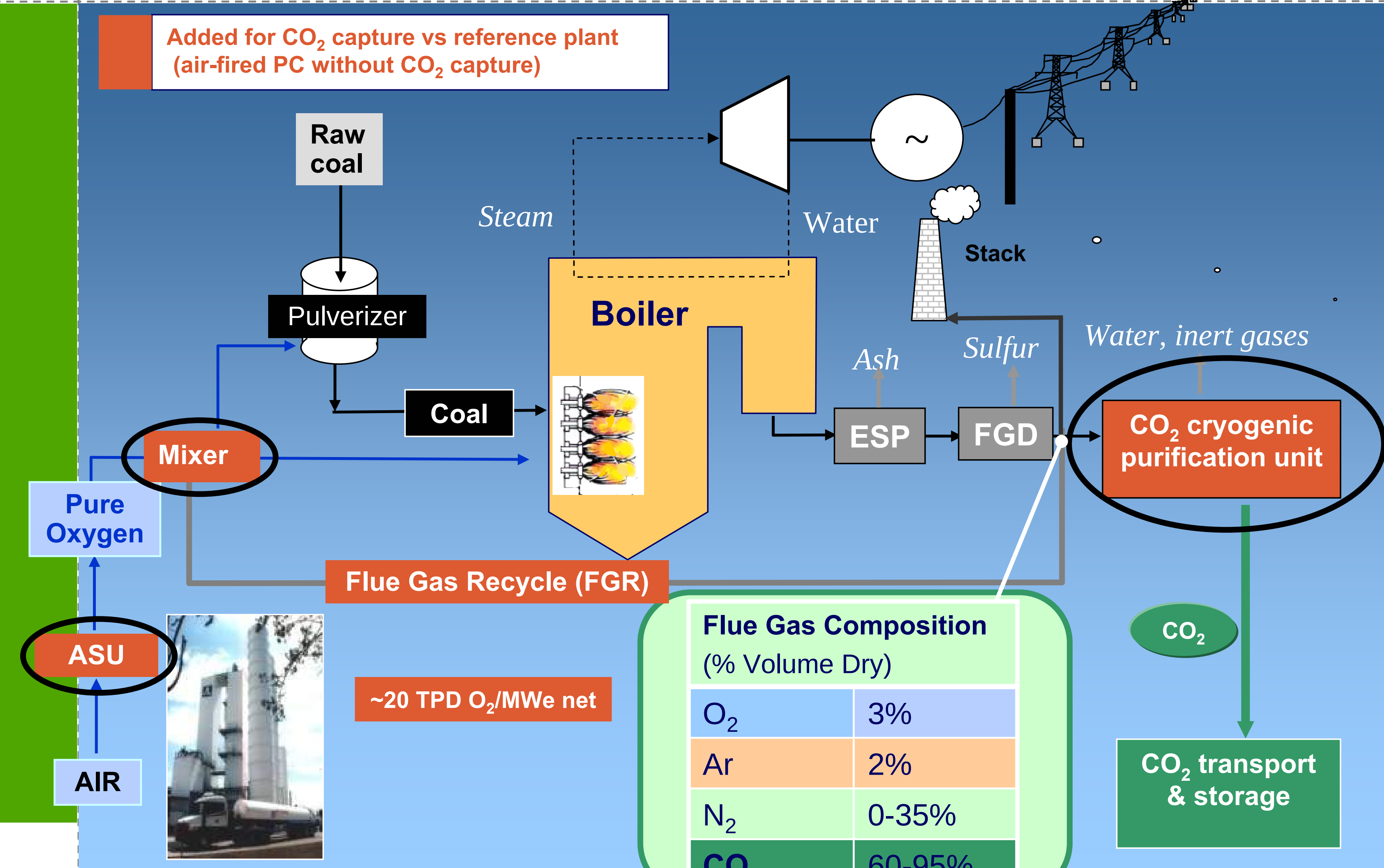




ASU and CO2 CPU for Oxy-Combustion

Jean-Pierre TRANIER, Nicolas PERRIN, Arthur DARDE

IEAGHG international Oxy-Combustion Network – March 5th, 2008

Oxy-Combustion for CO_2 Capture on PC boilers



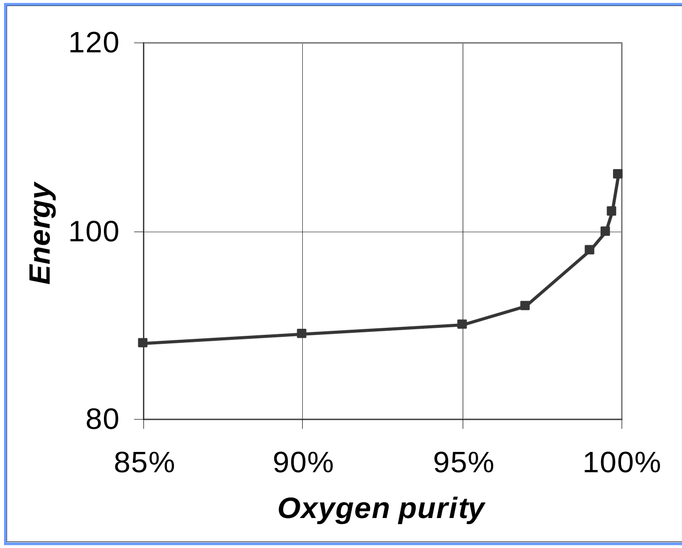
Flue Gas Composition
(% Volume Dry)

O_2	3%
Ar	2%
N_2	0-35%
CO_2	60-95%

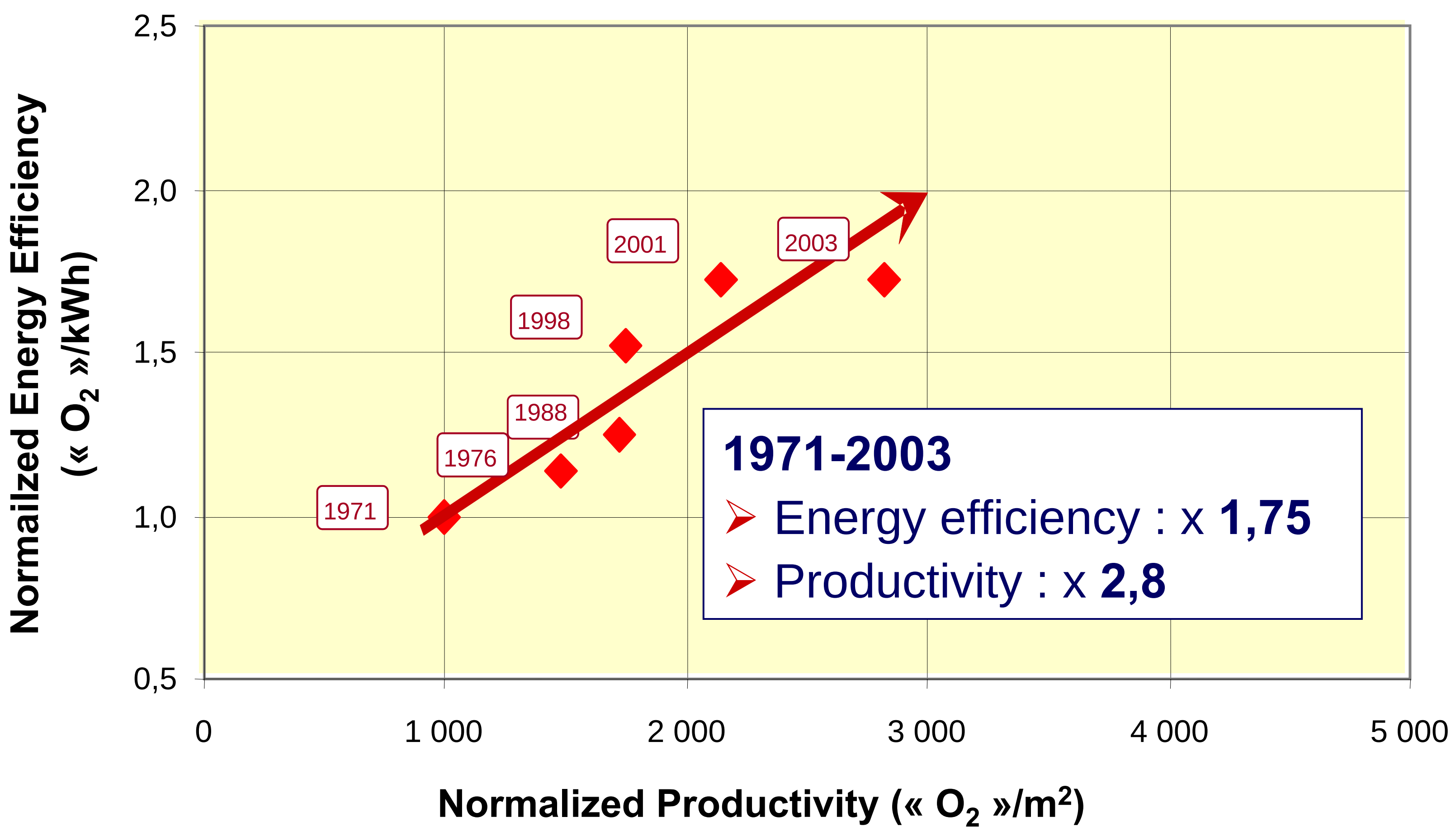
Air Separation Unit : background

- The **only** available technology for oxygen production in large quantities is **cryogenic** separation today
- Air Liquide offers cryogenic ASUs where a single train can produce **5000 metric tons per day of oxygen** with no duplication of equipment ;

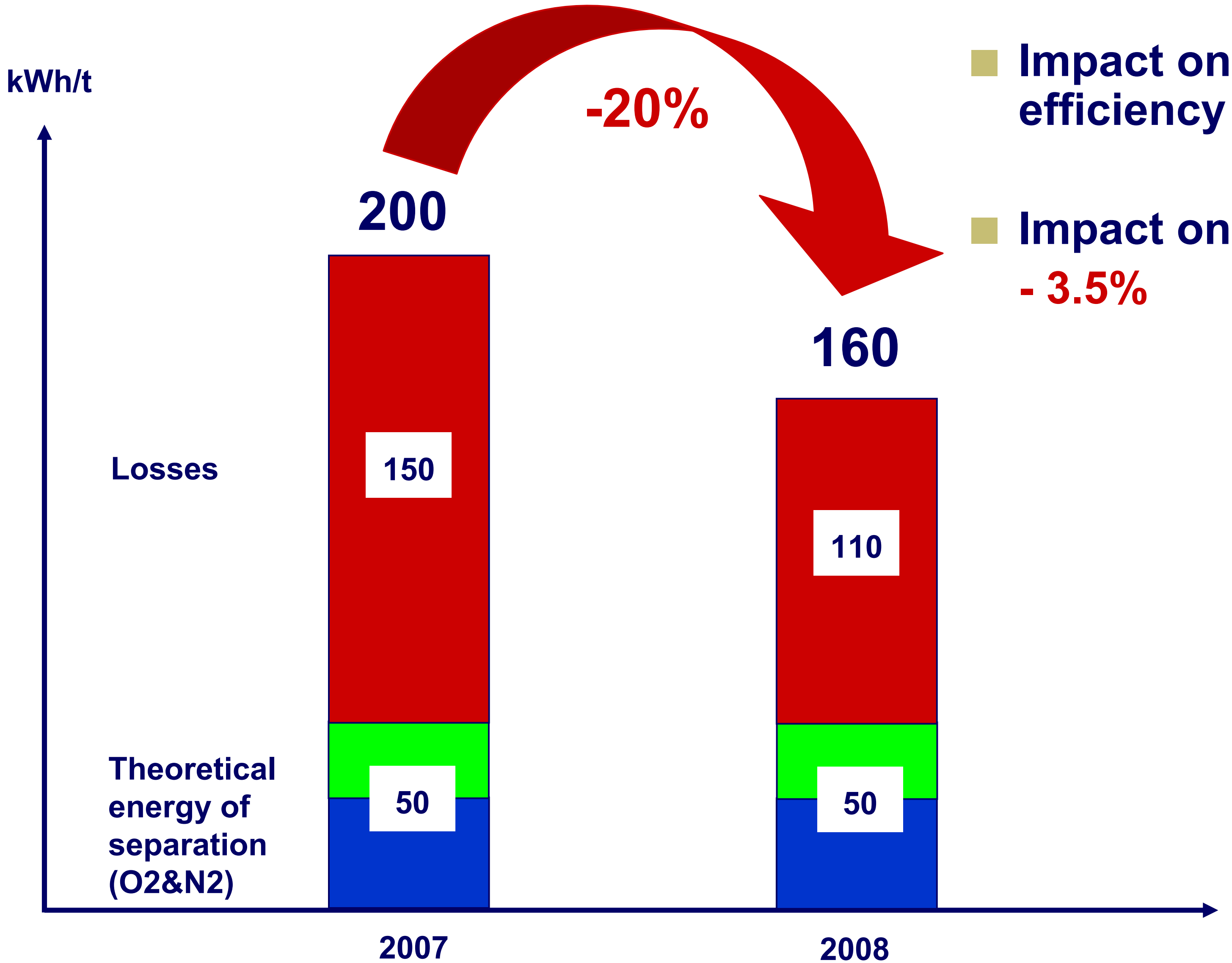
  In a multiple trains configuration, our largest reference is totaling **40000 t/d**
- Optimum **oxygen purity** for oxycombustion is in the **85-98%** range
- Cryogenic production of oxygen has been used for more than **100 years** but it is **still improving**



30 years of continuous Cryogenic ASU improvements

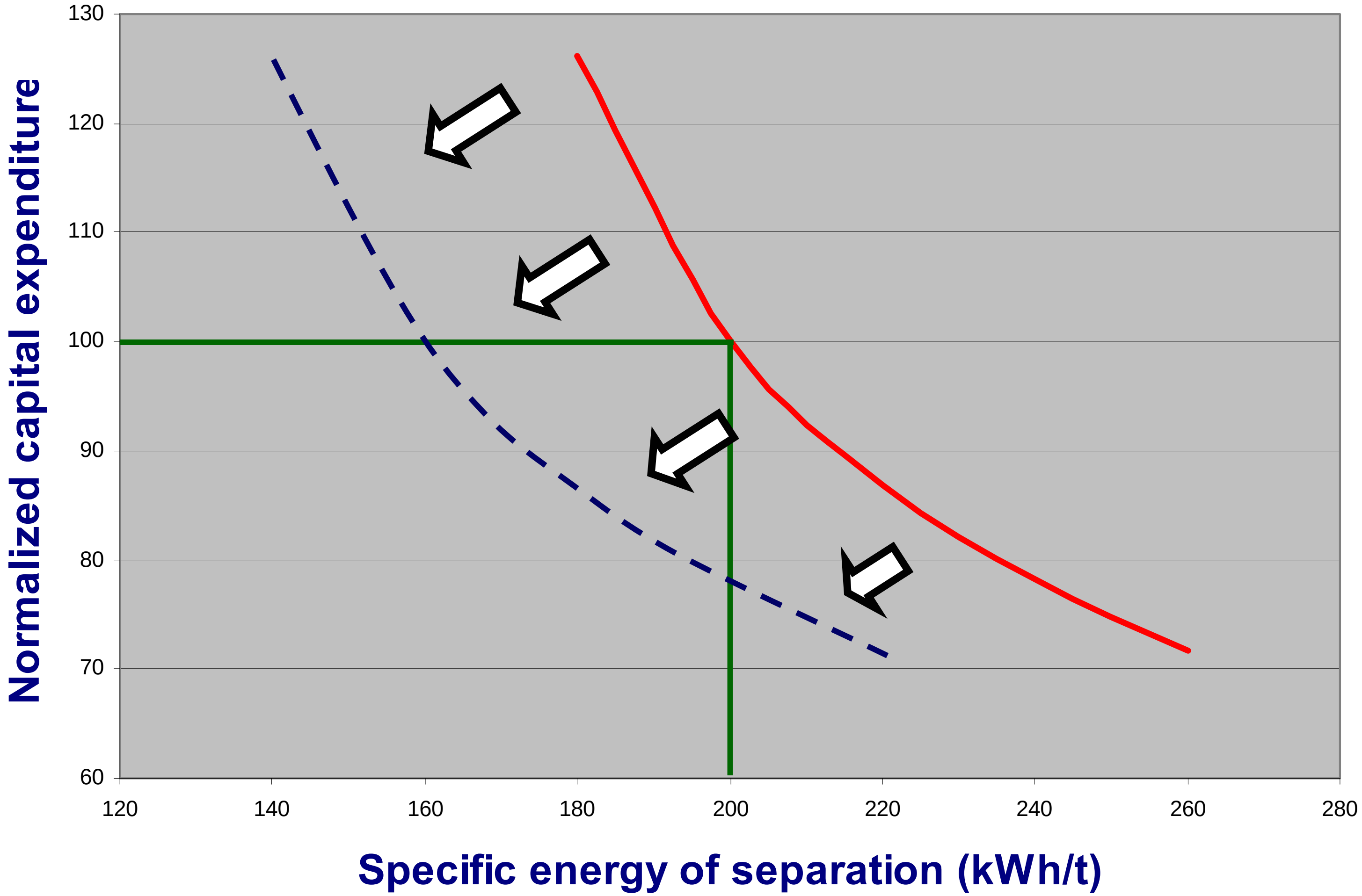


Specific energy of separation in kWh per ton of oxygen



- Impact on HHV efficiency : +1 %
- Impact on COE : - 3.5%

Key parameter in the optimization of an ASU : trade-off between CAPEX and OPEX



Heat integration

- Transfer of heat from the ASU compressor(s) to the steam cycle (this option can also be applied to the CO_2 compressor) can significantly reduce the losses associated to compression (and separation)

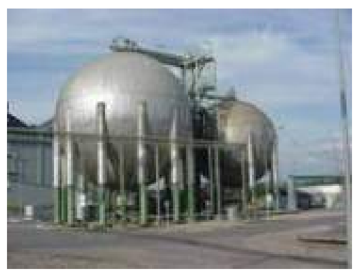
- This transfer can be direct (feed water preheating) or indirect (oxygen preheating, coal drying, any fluid of the cycle)

- For air and flue gas/CO_2 compression, several configurations are possible :
  - "Isothermal" compression with intercoolers after each stage
  - "Adiabatic" compression with cooling only after final stage
  - Intermediate configuration with intercoolers after 2 or 3 stages of compression

- These optimizations needs to be carefully studied in order to optimize CAPEX and OPEX for the overall oxycombustion cycle

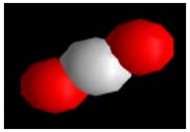
CO_2 CPU : background

- **Over 50 years of experience in CO_2 purification and liquefaction**
- **67 plants worldwide**
- **Markets : food, beverages, welding…**

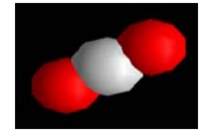
- **Key parameters for the right design of the unit :**
  - **Impurities in flue gas (PM, SO_x, NO_x, Hg, N_2…)**
  - **CO_2 product specification**
  - **Targeted CO_2 recovery**
  - **Trade-off CAPEX vs OPEX**

CO2 CPU development : 2 axis



1. **Confirm feasibility**

2. **Improve performance in term of CO2 recovery, specific energy and CO2 purity**

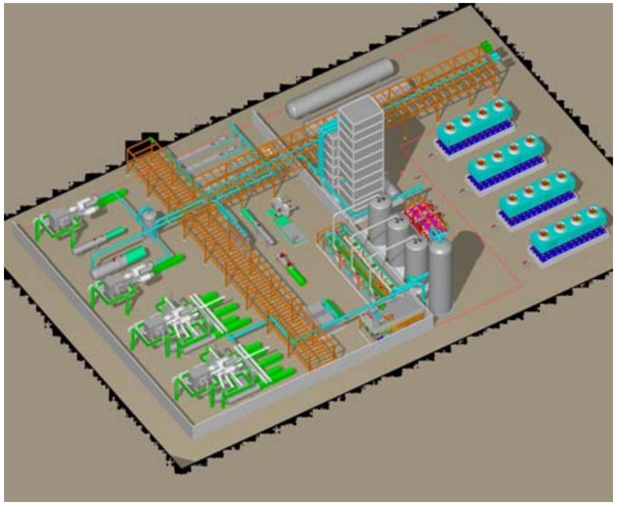


Confirm feasibility : simulations and laboratory tests

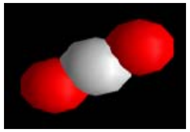
- **Thermodynamic :**
  - Molecular simulations
  - Simulation of the solubility of N_2O_4 in liquid CO_2 using the extension of the model of Scatchard-Hildebrand proposed by Myers-Prauznitz
  - Experimental measurements (sponsored by ANR AGENCE NATIONALE DE LA RECHERCHE)
    - Binary mixtures : CO_2-SO_2, CO_2-NO_2/N_2O_4, CO_2-NO, CO_2-Ar, SO_2-NO_2
    - Ternary mixtures : CO_2-SO_2-O_2, H_2O-CO_2-Ar, H_2O-CO_2-SO_2, CO_2-Ar-O_2
  - Equation of state selection and calibration
- **Flue gas scrubbing with various reagents**
- **H_2O removal with acid-resistant adsorbents in a CO_2 matrix with SOx and/or NOx**
- **Hg removal with various adsorbents in a CO_2 matrix with SOx and/or NOx**

Confirm feasibility : Saskpower case

- Basic Engineering Study performed for Saskpower :
  - Heat & Mass Balances, Process Flow Diagrams, PIDs, piping layout and material take-off, equipment specifications and RFQs have been developed
- Technologies of all pieces of equipment identified and validated
- Risk assessment study performed



Performance : basic findings

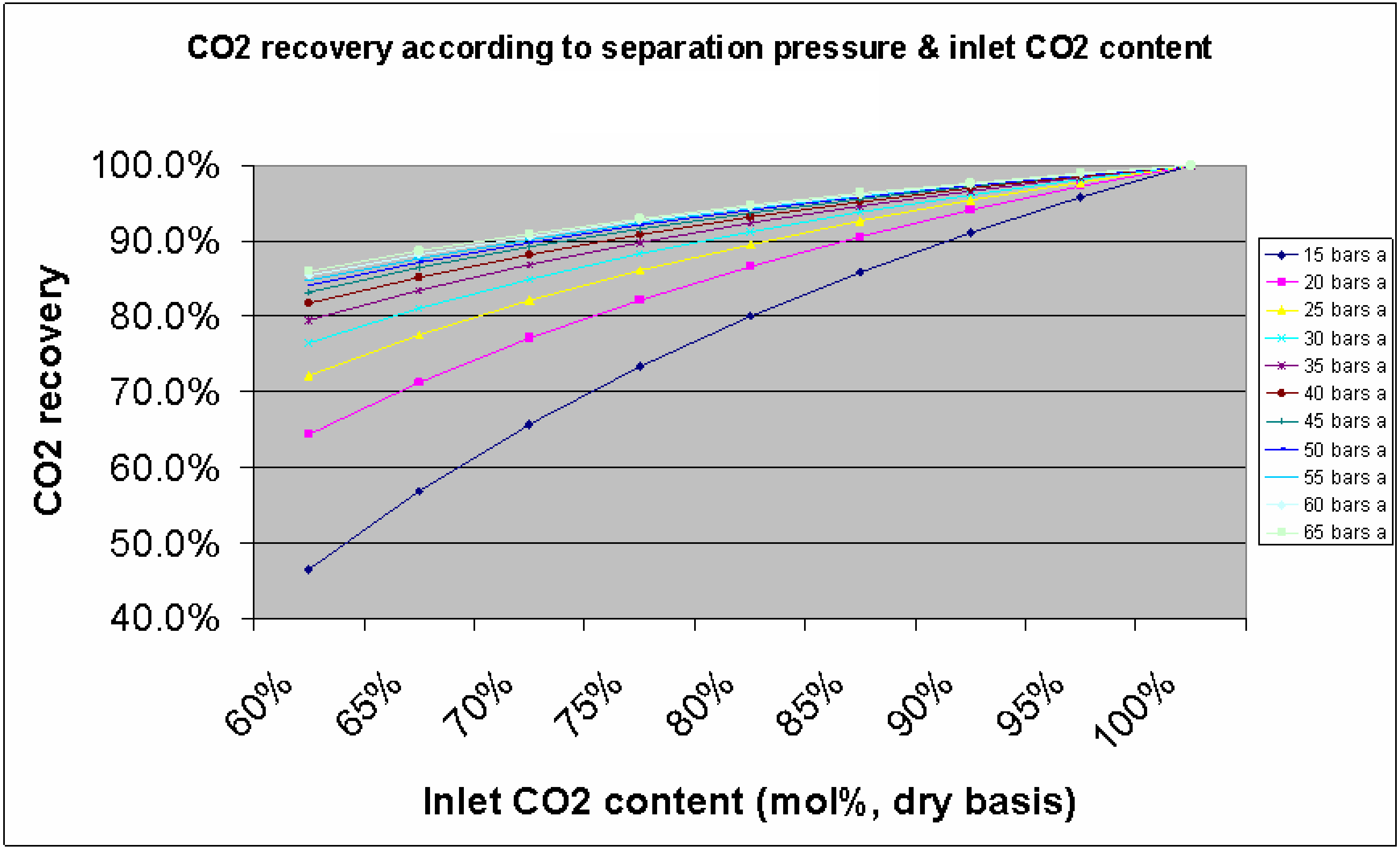


- Extensive studies on process cycles have been performed and **major improvements have been found compared to published studies**

- Two options :
  - non cryogenic : water removal only
  - Cryogenic purification : CO_2 specification is not anymore an issue

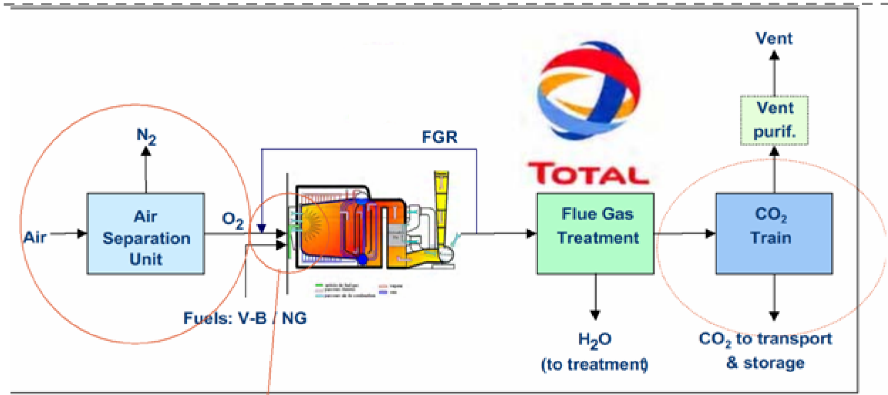
- **Cryogenic purification of flue gas decreases specific energy** because CO_2 can be condensed at a lower pressure and therefore be pumped instead of compressed

Performance : CO2 recovery versus CO2 content in flue gas (dry basis)



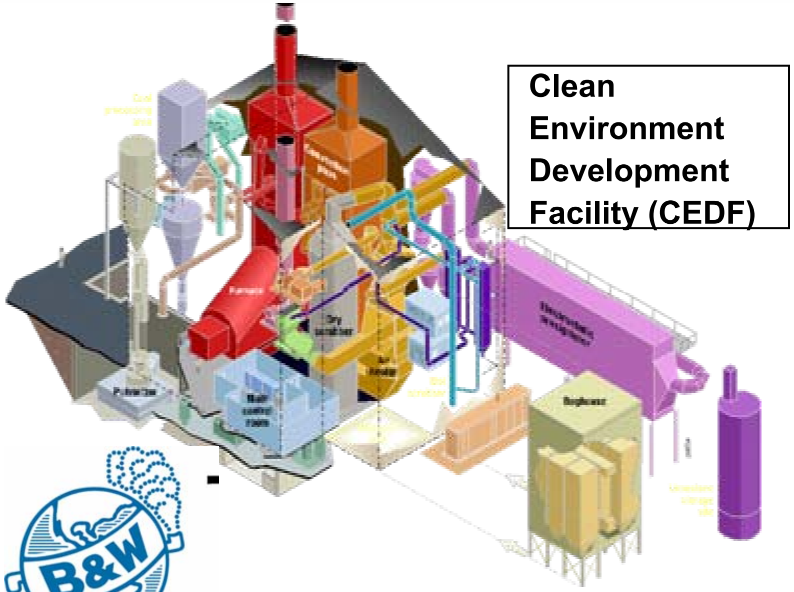
Pilot plants

- 30 MWth CEDF : 1st worldwide full oxy demo at this scale with B&W (USA)
- ASU & CO2 CPU for Callide Oxyfuel Project (Australia)
- Oxy-burners and CO2 purification for Total in Lacq (France)



R&D

Callide OxyFuel Project



B&W™

Conclusions

- Air Separation Unit : improvement in performance is available now

- CO2 CPU : feasibility is confirmed but design will remain conservative until pilot plants are started ; significant improvements in performance are achievable for cryogenic unit

- Integration of ASU and CO2 CPU in the overall oxycombustion plant are key to achieve high efficiency and low capital expenditure

THANK YOU
FOR YOUR ATTENTION

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Specific energy of separation : definition

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- Power required to produce 1 metric ton of pure oxygen contained in a gaseous oxygen stream at a given oxygen purity at atmospheric pressure (101325 Pa) under ISO conditions (15°C, RH 60%)
- Driver efficiency (EM, ST, GT) not taken into account : power at shaft
- Heat of regeneration of driers (steam, natural gas or electrical) not included
- Power consumption of cooling system (CW pumps, fans,…) not included
- Specific energy of production = Specific energy of separation + specific energy of compression
- Specific energy of compression ≈ 0.1xQ(Nm3/h)x$\log_{10}(P_{GOX}/P_{ATM})$
  - 1 t/h of GOX ≈ 1000 / 1.427637 ≈ 700 Nm3/h
  - For 1.4 bar abs : 10 kWh/t of pure O2

Consideration for Removal of non-CO_2 components from CO_2 Rich Flue Gas of Oxy-Fuel Combustion

IEA Oxyfuel Workshop

Yokohama March 4, 2008

Marie Anheden*, Stina Rydberg** and Jinying Yan*

*Vattenfall Research & Development AB

**Vattenfall Power Consultant AB

Outline of presentation

- Background
  - Sources of non-CO_2 components
  - Basis for evaluating the impact
- Technology options to meet different CO_2 specifications
  - Scenario descriptions
  - Technology
  - Cost implications
- Continued work

Where do the non-CO_2 components in the CO_2 come from?

The sources of non-CO2 components in the CO_2 stream are:

1. Fuel
   - H_2O, CO, SO_x, NO_x, H_2S,HCl, HF, H_2S, H_2, CH_4, heavy metals, hydrocarbons, particulates
2. Air or oxidant used for combustion of the fuel
   - O_2, N_2, Ar
3. In-leakage of air into the CO_2 capture system when it is operating at sub-atmospheric conditions
   - O_2, N_2, Ar
4. The CO_2 capture or CO_2 clean-up process
   - NH_3, solvents

The components and concentrations are in turn dependent on which capture process is used, and the selected CO_2 clean-up processes

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Capture technology options

- CO_2 quality is mainly an issue for oxyfuel and pre-combustion technology
- Postcombustion produces a relatively clean CO_2, 99%+
- In oxyfuel the CO_2 quality is a strong design parameter
  - Inert components from O_2 and air inleakage (oxidising conditions)
  - SO_x, NO_x removal level
  - Trace elements
  - Corrosive elements
- In precombustion the process selection and design requirements strongly inflences the quality
  - Reducing components H_2S, CO, H_2
  - hydrocarbons

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Impact of non-CO_2 components

- The CO_2 quality has implications in all the steps of the chain: Capture, Transportation and Storage
- The limiting factors will be different in each part
- It is a challenging task to actually defining these limitations

Proposed position: CO_2 quality

- **Limits on CO_2 quality should not be general but focus on identified harmful components and be based on a limit value that can be motivated**

- CO_2 of high purity can at least in theory be produced, however this has as a consequence
  - Increased energy consumption for the purification process. More fuel has to be used to produce the same amount of electricity
  - Increased investment and operational costs. The cost of CCS will increase
  - Decreased CO_2 recovery. CO_2 may be lost as a consequence of the clean-up process

- It is important to recognise that the technology for CO_2 capture and clean-up has not yet been demonstrated in practice in a power plant application
  - more real life operational experience is required
  - Specifically, the cryogenic clean-up step required to remove non-condensable gases (mainly Ar, O_2, N_2) in the oxyfuel technology is not tested

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Evaluating the concentration levels, strategy for assessment –CCS chain

The allowable levels of non-CO_2 components in CO_2 to be stored has been evaluated based on the following aspects

1. Measures to avoid operational problems during CO2 processing
2. Measures to avoid operational problems during CO_2 transport
3. Measures to avoid operational problems during CO_2 injection
4. Storage integrity (requires site specific investigations)
5. Environmental aspects over the lifetime of the full capture transport and storage chain
6. Health and safety aspects of the full chain
7. Legal aspects
8. Economic considerations

In general it has been found that the limit values based on occupational exposure limit values used to assess the dangers in case of leakage to air puts the most severe restriction and is easiest to quantify

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Oxyfuel technology development
CO_2 quality scenario study

Oxyfuel technology development

- What has been done?
  - In cooperation with external suppliers we have studied the FGD, FGC, WESP and CO_2 purification and compression for different Oxyfuel scenarios
- Why?
  - To fill gaps in the knowledge concerning the cleaning and preparation of flue gases from Oxyfuel combustion
- Scenarios were defined with basis in different fuels and different CO_2 transport and storage options (=different CO_2 product quality)

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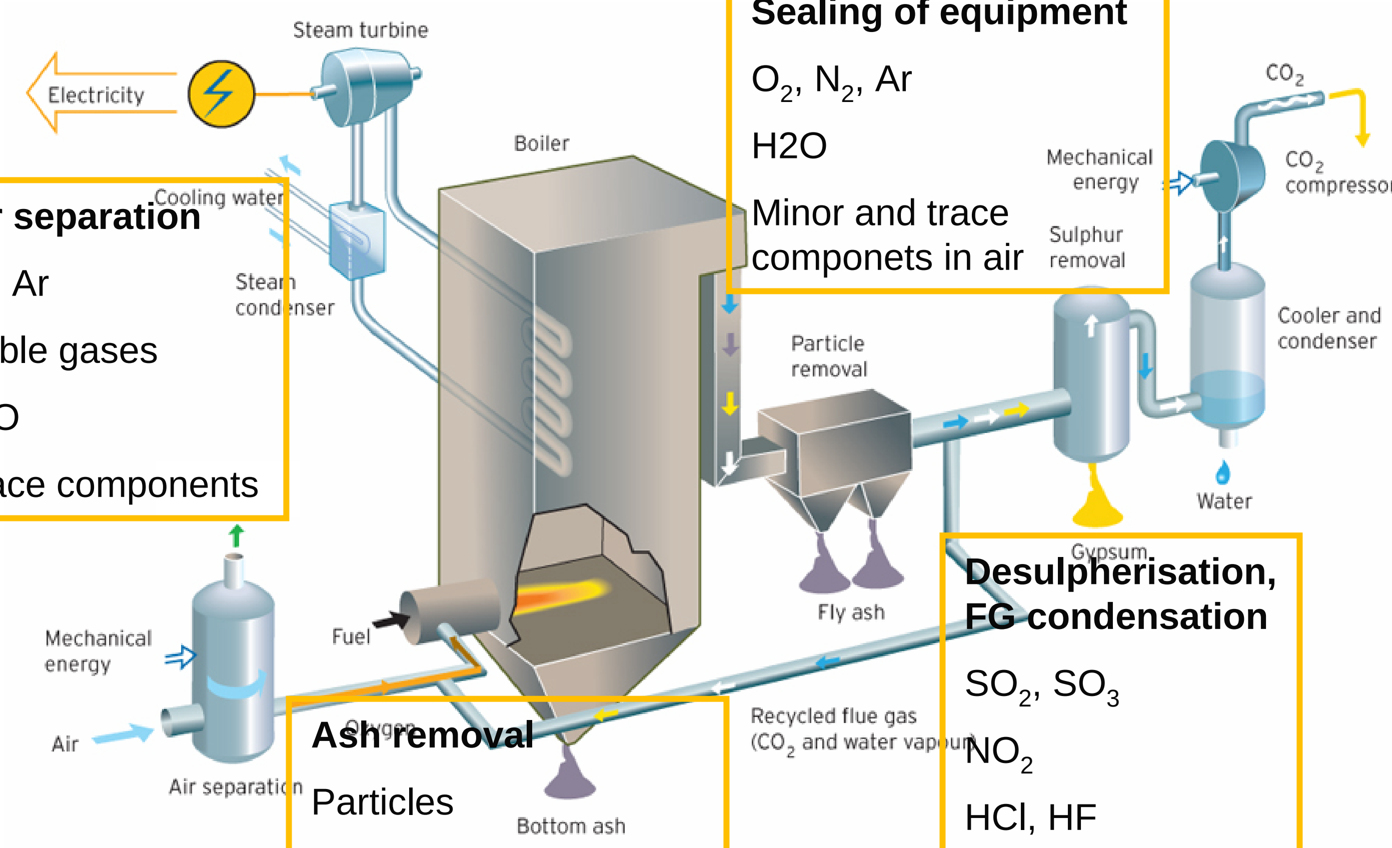
Oxyfuel combustion, main removal options



Air separation

N_2, Ar

Noble gases

H_2O

Trace components

Sealing of equipment

O_2, N_2, Ar

H2O

Minor and trace componets in air

Ash removal

Particles

Heavy metals

Acidic components (SO_2, SO_3, HCl, HF)

Desulpherisation, FG condensation

SO_2, SO_3

NO_2

HCl, HF

Particles

$HgCl_2$

Cd, Tl

Sb, Sn

CO2 compression, purification

Intercooler scrubbers

SO_2, SO_3

NO, NO_2

Hg

Carbon filter

Hg, other trace elements

Acidic components

Dryers

H_2O, ?

Phase separation

N_2, O_2, Ar, noble gases

NO

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Scenario definition – Scenario 1

- Large scale (~1000 MWe, gross) Lignite fired condensing power plant
- Pipeline transport
- Aquifer storage
  - CO_2 product pressure 110 bar, temperature 50 DegC

- Modest CO_2 quality requirements
  - CO_2 > 96 vol%
  - H_2O < 500 ppm
  - SO_2 < 200 mg/Nm3
  - O_2 < 4 vol% (total inerts)

Scenario definition – Scenario 2

- Large scale (~ 650 MWe, gross) Bituminous coal fired condensing power plant
- Pipeline transport
- On-shore storage
  - Low O_2 content
  - CO_2 product pressure P = 110 bar
  - CO_2 product temperature T = 50 DegC

- High CO_2 quality demands
  - CO_2 > 96 vol%
  - H_2O < 50 ppm
  - O_2 < 100 ppm
  - SO_2 < 50 mg/Nm^3

Scenario definition – Scenario 3

- Large scale (~ 620 MWe, gross) Bituminous coal fired power plant
- Ship transport
- Off-shore storage (EOR?)
  - CO_2 product pressure P = 7 bar
  - CO_2 product temperature T = -50 DegC

- Very high CO_2 quality demands
  - CO_2 > 96 vol%
  - H_2O < 5 ppm
  - O_2 < 100 ppm
  - SO_2 < 5 mg/Nm^3
  - NO_x < 5ppmv

Scenario CO_2 quality specifications

	Modest CO_2 quality	High CO_2 quality	Very high CO_2 quality
CO_2	>96 vol%	>96 vol%	>96 vol%
H_2O	<500 ppm	<50 ppm	<5 ppm
SO_2	<200 mg/Nm³	<50 mg/Nm³	< 5 mg/Nm³
O_2	Total inerts < 4 vol%*	<100 ppm	<100 ppm
NO_x	-	-	<5 ppm

* No individual restriction on O_2 content

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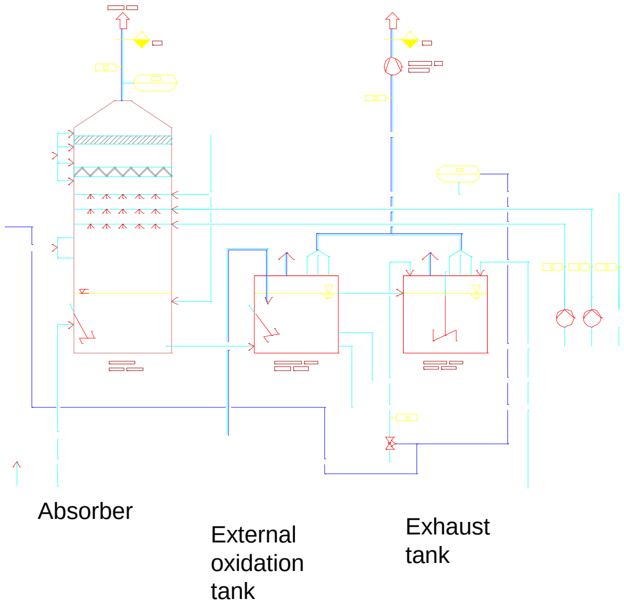
Flue gas clean-up I

- ESP – Electrostatic Precipitator
  - Scenario 1 hot + cold ESP
  - Scenario 2-3 cold ESP

- FGD – Flue Gas Desulphurisation
  - open tower wet scrubber, limestone slurry
  - High demand of SO_2 removal (up to 99.9%), high L/G ratio
  - pH
  - Also removes HF/HCl, SO_3, fly ash, heavy metals…
  - To avoid air ingress, the oxidation tank is separated from the absorber



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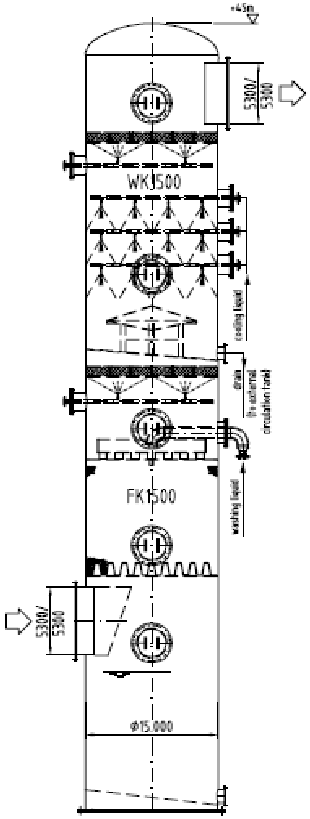
Flue gas clean-up II

- FGC – Flue gas condenser
  - Cooling, drying and cleaning
  - Designed as a direct condenser in two stages
    - Packed bed scrubber with possibility to dosing of NaOH to remove acidic components (SO_2)
    - Open spray tower
    - Cooling to 25C
    - Demister
- WESP
  - Possibility to remove aerosol and SO_3
  - Not included in scenario 1-3



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CO_2 compression, purification

- Compression
- Cooling to remove water and reduce compression power requirements
- Inerts removal
  - Reducing air in-leakage increases CO_2 capture rate
- Possibility of SO_x and NO_x, Hg removal (ref. Air Products)
  - converted and removed as dilute acid streams
- O_2 removal, CO_2 recovery
  - Membrane on vent stream to separate O_2 and CO_2 and bring back to boiler

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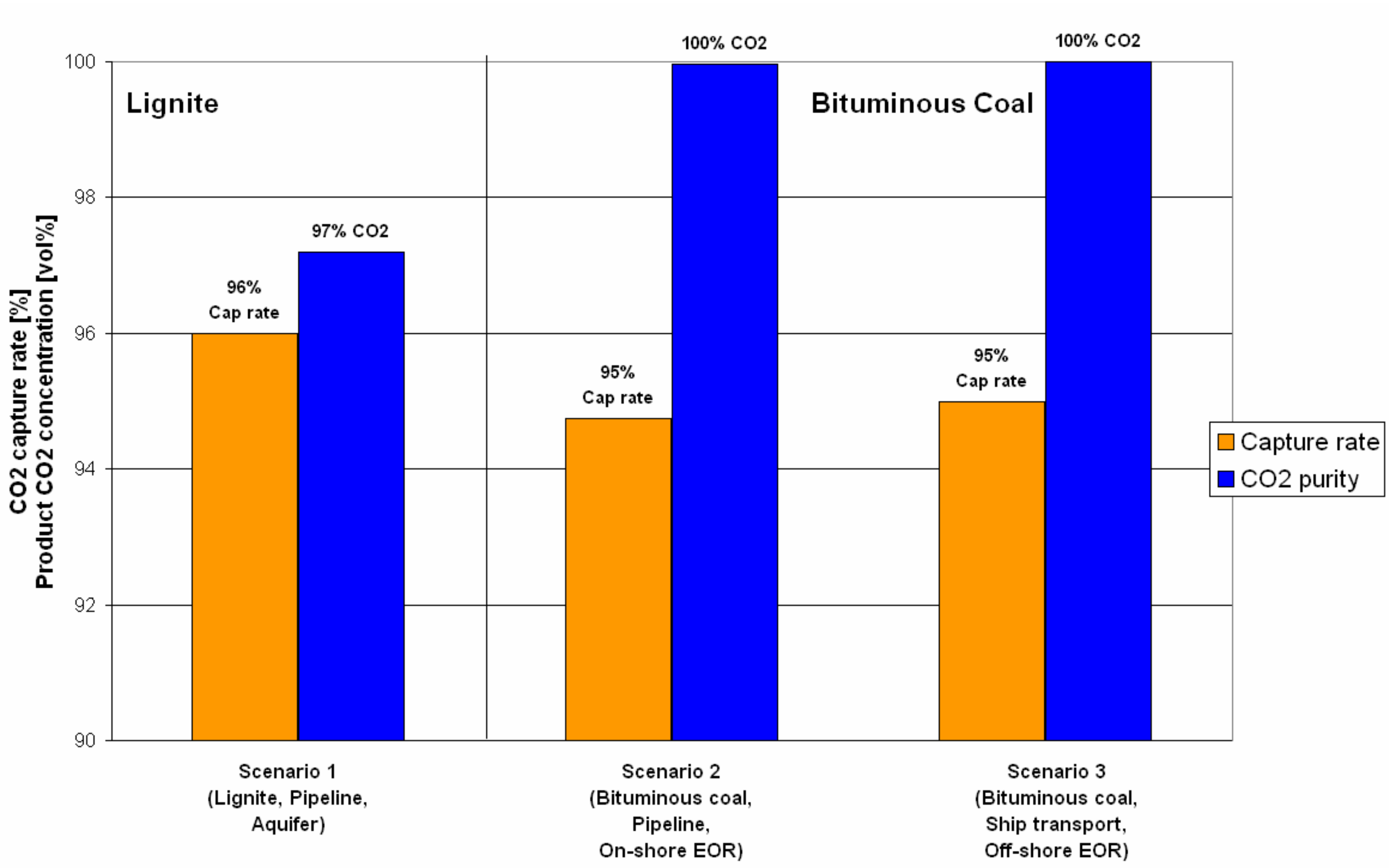
Results – CO_2 Capture rate and product CO_2 concentration



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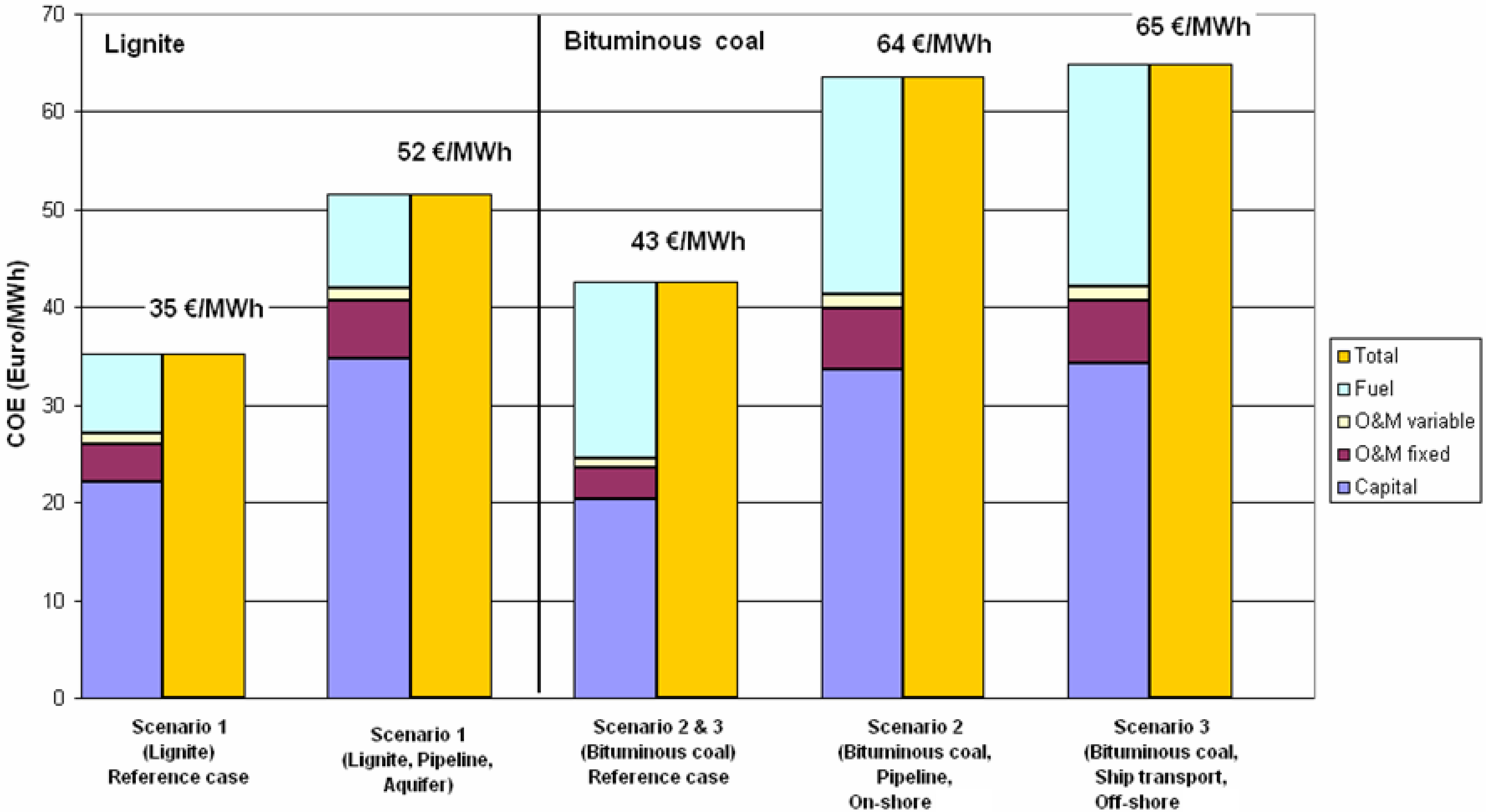
Results – COE



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Results – COE II

- Prerequisites:
  - Real interest rate 8%
  - Depreciation time 25 years
  - 7 500 full load hours / year
  - Fuel price: 4 €/MWh for lignite
    8,3 €/MWh for bituminous coal
- Results:
  - Capital costs dominate
  - Higher fuel cost than reference case, due to lower efficiency
  - Fixed O&M costs (personnel, maintenance, insurance etc) increase, due to more equipment
  - Larger, relative COE-increase for Scenarios 2 & 3

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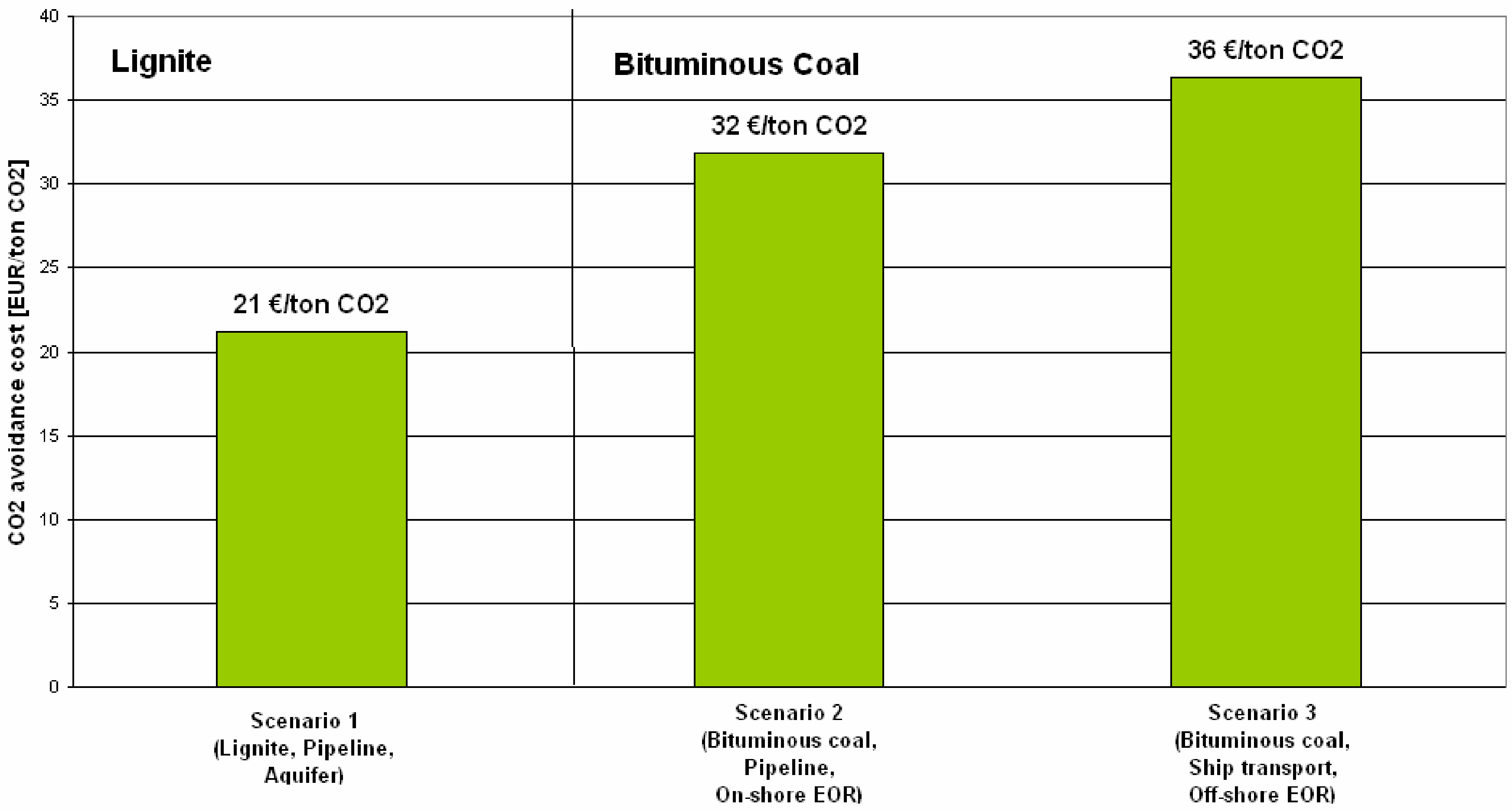
Results - Avoidance cost



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Conclusions

- The technology to reach very high purity is available
  - Verification in Oxyfuel environment however required
- Identified possibility of SO_x and NO_x removal in the CO_2 compression part
  - Verification required
- Ship transport CO_2 quality possible at reasonable cost
- Weaker connection between CO_2 product purity and cost than expected (<5% of COE)
- Demand for extremely low O_2-concentration in the product is possible to meet
  - complexity and cost of the CO_2 compression process increases
  - capture rate decreases
  - Verification required
- Increased confidence in performance and costs for the flue gas treatment

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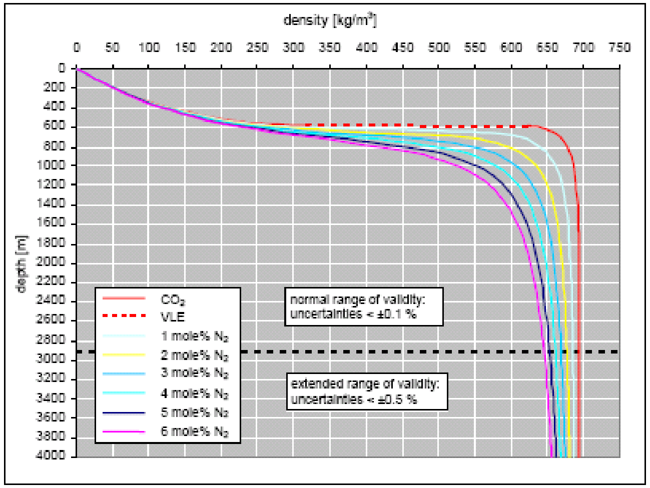
Continued work (under planning)

- Validation of flue gas cleaning equipment in oxyfuel environment in the Schwarze Pumpe pilot
- Effect of inert components (N_2, Ar, O_2, …) on volume efficiency and economics of transport and storage compared to cost of removal
  - CO_2 volume calculation for realistic CO_2 composition scenarios for oxyfuel with different clean-up and processing levels (scenarios based on previous work)
  - Impact on total transport and storage volume for relevant transport and storage scenarios (different T and p)
  - Economic assessment
- SO_2/SO_3 conversion
- Corrosion testing for boiler, process and pipeline material selection



Thank you for your attention!

Questions?

Further work on the Oxyfuel Capture technology

- Validation of results in lab scale and pilot plant
  - Combustion characteristics
  - Pollutants formation and destruction or removal in different components
  - Component operating characteristics and interaction with overall plant
- Material selection / Corrosion risk in the oxyfuel plant, from furnace to CO_2 compression part
- CO_2 quality demand with reference to O_2 content and other components
- Part load behaviour of the oxyfuel plant
- Thorough discussion on the impact from air in-leakage
- Overall optimisation of the process
- Scale-up to demonstration plant (250-350 MWe)

What are the effects, CO2 capture and processing

- Corrosion
  - H_2O, SO_x, NO_x, O_2, H_2S, HCN, HF, HCl
- Effect on thermo-pysical properties
  - All components
    - Phase equilibrium
    - Density
    - Enthalpy, entropy
    - …
- Hydrate formation
  - H_2O, CO_2, H_2S, CH_4

- Internal energy consumption and investment of cleaning the CO_2 to different levels

What are the effects on CO2 transport and storage, I

Pipeline transport

- Corrosion (operation, cost of pipeline, economy)
  - H_2O, SO_x, NO_x, O_2, H_2S, HCN, HF, HCl
- Hydrate formation (operational problem, risk of plugging)
  - H_2O, CO_2, H_2S, CH_4
- Two-phase flow (operation)
  - Ar, O_2, H_2, H_2S
- Leakage of toxic components (health and safety, legal)
  - H_2S, COS, CO, SO_2, NO_x, heavy metals.
    Requires safety measures to minimise risk.
- Odour (health and safety, legal)
  - H_2S, mercaptanes
- Fouling of pipe (operational problem)
  - particles
- CO_2 transport volume efficiency (economy)
  - O_2, Ar, N_2

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What are the effects on CO2 transport and storage? II

Injection facilities

- Corrosion (operation, cost of injection pipe and equipment, economy)
  - Acid-forming compounds, SO_2, NO, H_2S, CO, HCN, HF, HCl, together with water and O2
- Hydrate formation (operational problem, risk of plugging)
  - CO_2, H_2S and CH_4 can form hydrates in presence of free water.
- Toxic compounds, in case of a leakage (health and safety, legal)
  - H_2S, COS, CO, SO_2, NO_x, heavy metals. Requires safety measures to minimise risk.

Storage in deep laying aquifers and depleted hydrocarbon fields (OBS! Site-dependant conditions)

- Blockage of pores and reduced permeability (operation problem during injection phase)
  - Particulates and O_2, H_2S, SO_2 through precipitation
- Dissolution of cementing carbonate minerals (operation and storage safety)
  - SO_2, H_2S, NO_x, HCl, HCN, HF
- Toxic compounds, in case of a leakage (health and safety, legal)
  - H_2S, COS, CO, SO_2, NO_x, heavy metals. Requires safety measures to minimise risk.

Caprock

- Chemical effects on brine and storage rocks. Depends on composition of caprock and aquifer water (operation, health and safety)
  - HCl, HCN, HF, H_2S, NO, SO_2, O_2

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What are the effects on CO2 transport and storage? III

Effects on environment and health

- Toxic compounds
  - H_2S, COS, CO, SO_2, NO_x, heavy metals (Hg), organic compounds (solvents, mercaptans). Requires safety measures to minimise risk
- flammable compounds
  - such as H_2, CH_4
- Acidification
  - SO_2, NO_x, H_2S etc. can form stronger acids than CO_2
- Nutrients (eutrophications),
  - such as NO_x, N_2

The presence of other components than CO_2 in the transported/injected/stored gas stream may warrent increased safety measures and monitoring procedures.

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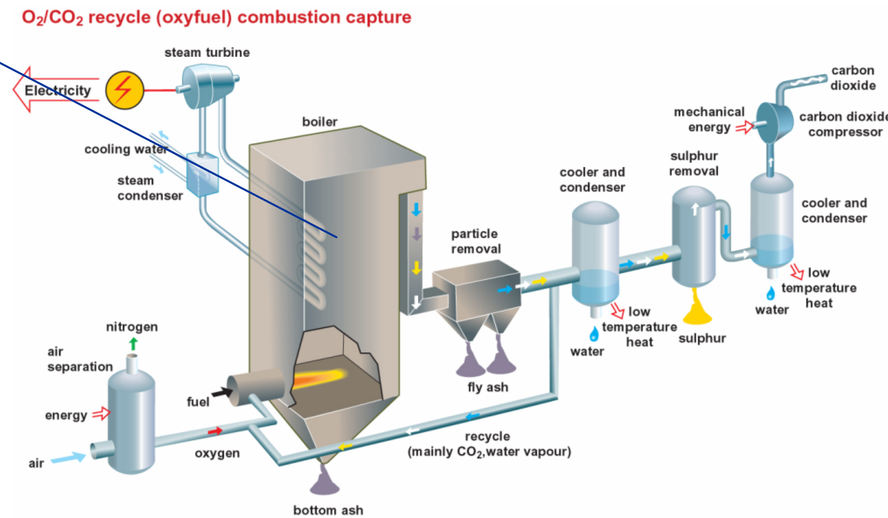
Examples of pilot investigations

- Combustion characteristics
  - -(NO_X; SO_X; CO, O_2-level, CO_2; SO_2; SO_3, Hg and HC along flame and boiler path)
- Behaviour of recirculated products in flame
- Flame characteristics
  - -(shape) and stability, mapping of these as well as species (O_2; CO; NO_X), temperature- and velocity profiles



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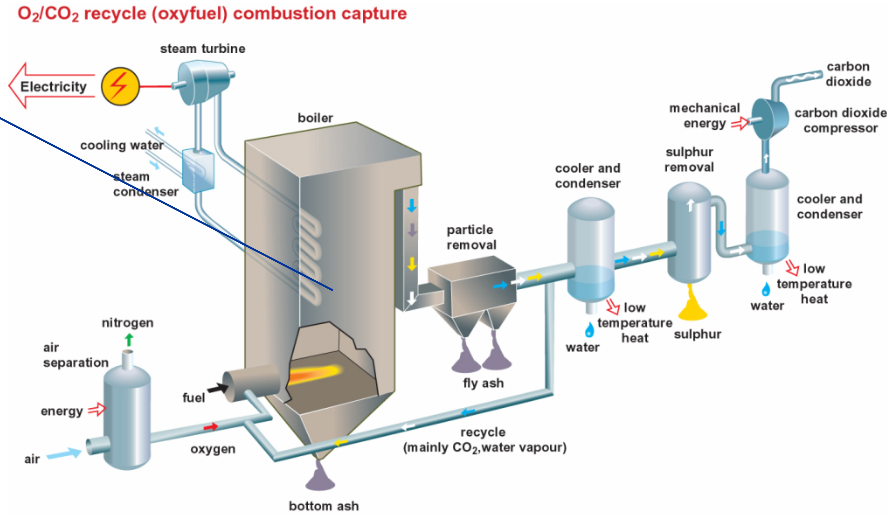
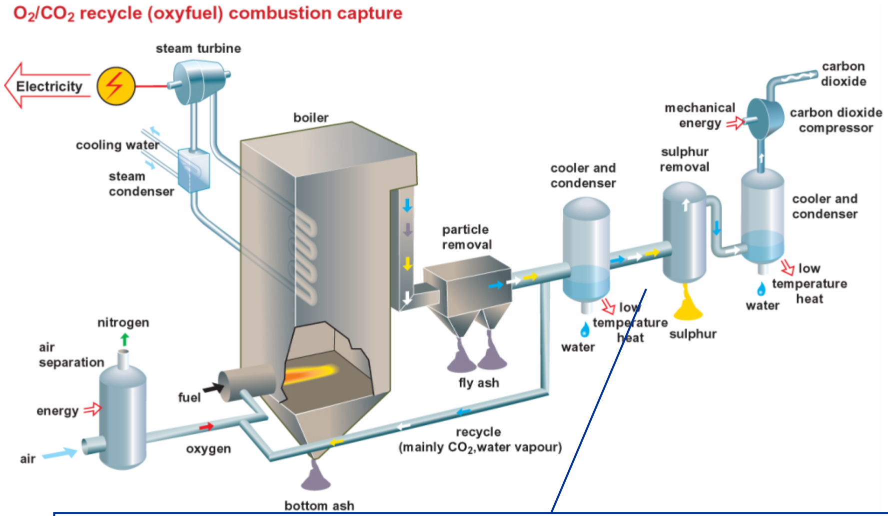
Examples of pilot investigations

- slagging/fouling
- ash quality
- radiation heat transfer in radiative section
- convective heat transfer in boiler convective section,
- Main loop air in-leakage / extracted gas quality
- Corrosion and material testing

- All these measurement should be done in air-firing and oxyfuel atmosphere



Examples of pilot investigations



- Separation rates of ESP, FGD and FGC at different flue gas compositions
- Acid dew point
- SO_2 and SO_3 concentration
- Distribution of trace elements

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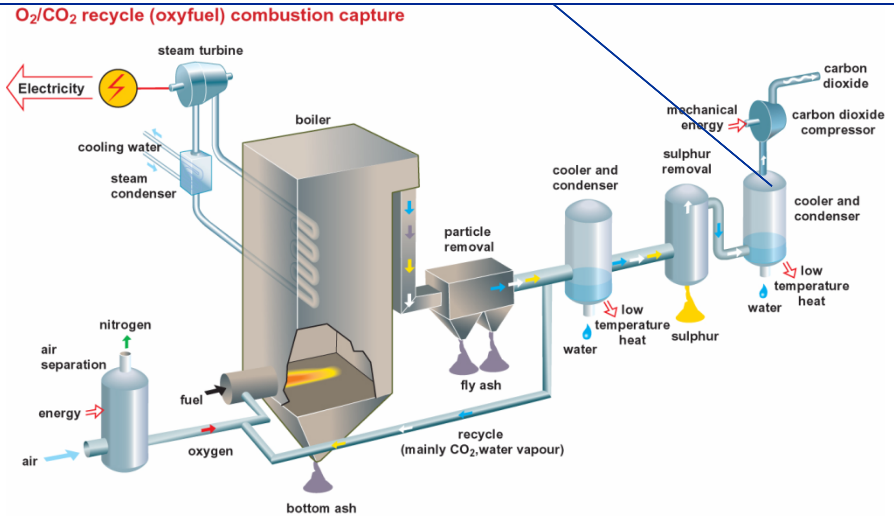
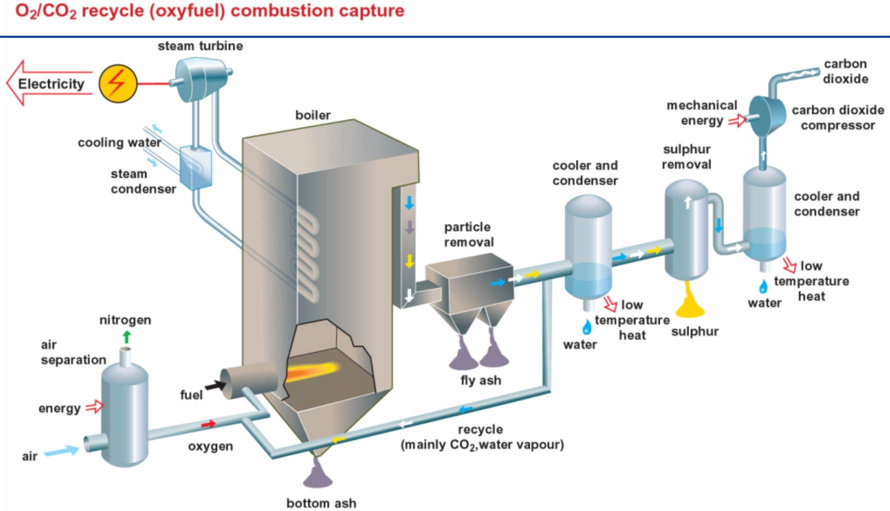
Examples of pilot investigations

- Effect of different levels of O_2, acidic components, water vapour on CO_2 compressor train
- CO2 product composition and capture rate
- Condensate quality, FGC and CO_2-compression train



Examples of pilot investigations

- Informations about the flexibility under the aspect of Load Changes
- Gathering of information of the complete system dynamics



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AIR PRODUCTS

Technical Considerations for a Very Large Scale Air Separation Unit for a Coal Fired Power Plant Application

Kevin Fogash
Air Products and Chemicals

IEAGHG International Oxy-Combustion Network
3rd Workshop
Yokohama, Japan
5 - 6 March 2008

Agenda

- Introduction to Air Products
- Very Large Air Separation Units
- Air Products' track record
- Air Products as a solution company
  - Air Separation Unit Integration to the Oxycoal process

Who Is Air Products?

- Global atmospheric, process and specialty gases, performance materials, equipment and services provider
- Serving industrial, energy, technology and healthcare markets worldwide
- Fortune 500 company
- Operations in over 40 countries
- ~22,000 employees worldwide
- Known for our innovative culture and operational excellence
- Corporate responsibility commitment




AIR PRODUCTS

Innovation-Driven

- **FY'07 R&D spending: $140 million**
- **Focus on creating value in high growth / emerging markets**
- **Applications focus is at the heart of our brand**
- **Alliances / technology partnerships with universities, labs, consortia, other companies**
- **Investments in venture capital funds to gain technology access**
- **Open Innovation approach**

AIR PRODUCTS

Sale of Equipment Overview

- Global presence - All Industries
- Extensive reference list – designed and built over 1,200 plants
- ASU operating know-how translated to a cost effective equipment solution
- Cryogenic plant offerings ranges from 50 to +5000 metric ton per day
- Value Added Options:
  - Increased engineering content
  - Construction advisory services
  - Commissioning services
  - Turnkey construction
  - Start-up and Operator Training services
  - Spare Parts support services
  - Operate and Maintain contracts

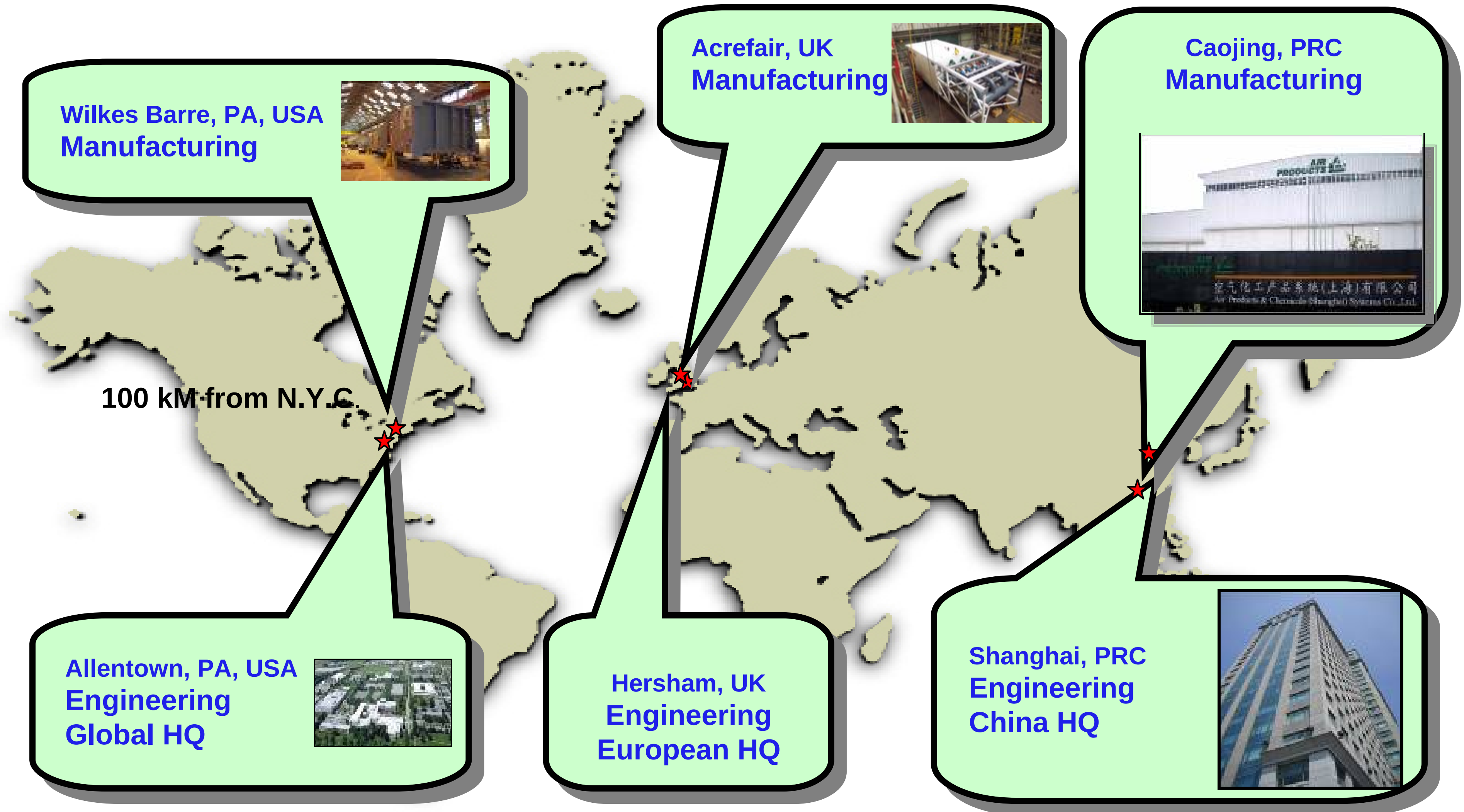
AIR PRODUCTS

"On-Site" – Sale of Gas Overview

- **Air Products designs and builds a plant adjacent to the customer or pipeline**
  - **Reduces schedule & capital cost risk**
  - **Allows integration of steam & power**
- **Plant investment by Air Products**
  - **Customer typically supplies land and utilities**
- **Operation and maintenance by Air Products**
  - **Safety**
  - **Proven supply reliability**
  - **Delivery, efficiency and availability guarantees**
  - **Potential co-product and scale benefits**
  - **Merchant oxygen, nitrogen, argon**
  - **Shared plant or pipeline systems**
- **Customer buys gas from the facility under a long-term agreement**
  - **Enables customer to focus resources and capital on core activities**

AIR PRODUCTS

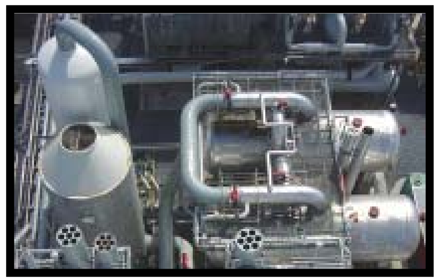
ASU Engineering and Manufacturing Locations



Overview Of The Process

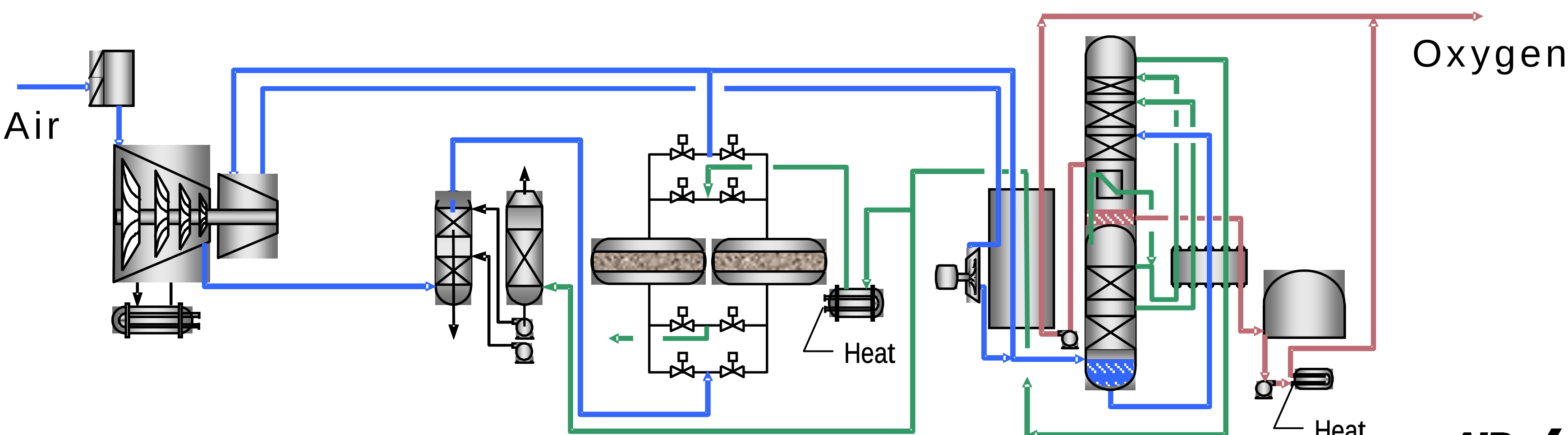
Main and Boost Air Compression

Air Cooling and Pretreatment



Cryogenic Separation

Storage



It is about more than just O2...

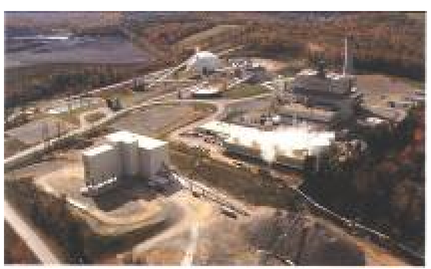
- **APPLICATION EXPERIENCE: Supplied large oxygen/air separation equipment to all type of applications and industries:**
  - **Power**
  - **Gasification**
  - **Metals**
  - **Refining / Petrochemicals**
- **INTEGRATION EXPERIENCE: Air separation plants in all integration modes—**
  - **Oxygen supply control system (Load following, start-up shutdown, peak-shaving)**
  - **MAC heat recovery**
  - **Standalone, nitrogen integrated, and air/nitrogen integrated (IGCC)**
- **MEGA-TRAIN EXPERIENCE: Operating very large single train air separation plants since 1997 in Rozenburg, The Netherlands (3250 MTPD); also installed a 2x3500 MTPD unit in Qatar**
- **RELIABILITY: First company to supply high-reliability tonnage oxygen for power projects without oxygen backup**
- **OTHER GAS PRODUCTS: Broad industrial gas industry experience creates synergies with H_2, CO, and CO_2 markets**

AIR PRODUCTS

Air Products and Power

- Long-term commitment to Power since the 80’s starting with the IGCC market
- Focused on safe, highly reliable, and economic ASUs
- Baytown: LASU + Back-end
  - Designed, built, own and operate syngas cleanup and separation facility (“back-end”) of heavy oil gasifier in TX

→ The result is a broad range of experiences for Power with Cogen (including coal), Gasification, and Syngas



88 MW
Ebensburg (Cambria), PA
USA

120 MW,
Orlando, FL
USA

55 MW,
Stockton,CA
USA

Syngas, CO, H2
Baytown, TX
USA

Very Large Air Separation Units

Very Large Air Separation Units

- **Air Products' long track record providing the train size required by the project**
  - **Market drives ASU scale-up**
- **Site requirements >5000 metric ton/day in single or multitrain configurations**
- **Challenging cycle design, engineering, installation, and manufacturing issues**
- **Best train solution based on customer's specific requirements**

VLASU Integration challenges to Oxycoal power plants

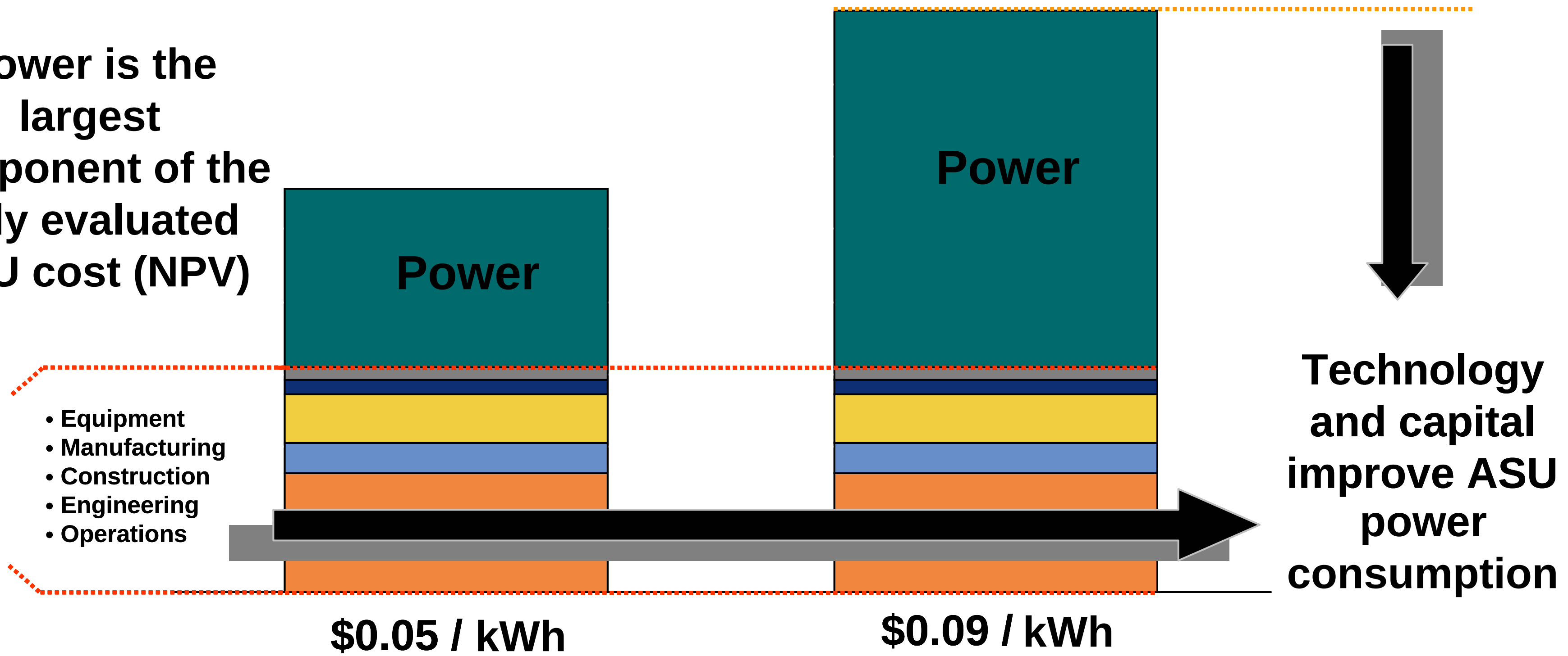
Number of trains based on customer's specific requirements:

- Power vs. Capital costs
- Transport of ASU(s) to site
- Reducing construction / erection costs and risks
- Operability
- Compression integration at large scale
- Fit with customer's use patterns
  - Turndown / ramping up
- Reliability, including spare parts handling
- Schedule

AIR PRODUCTS

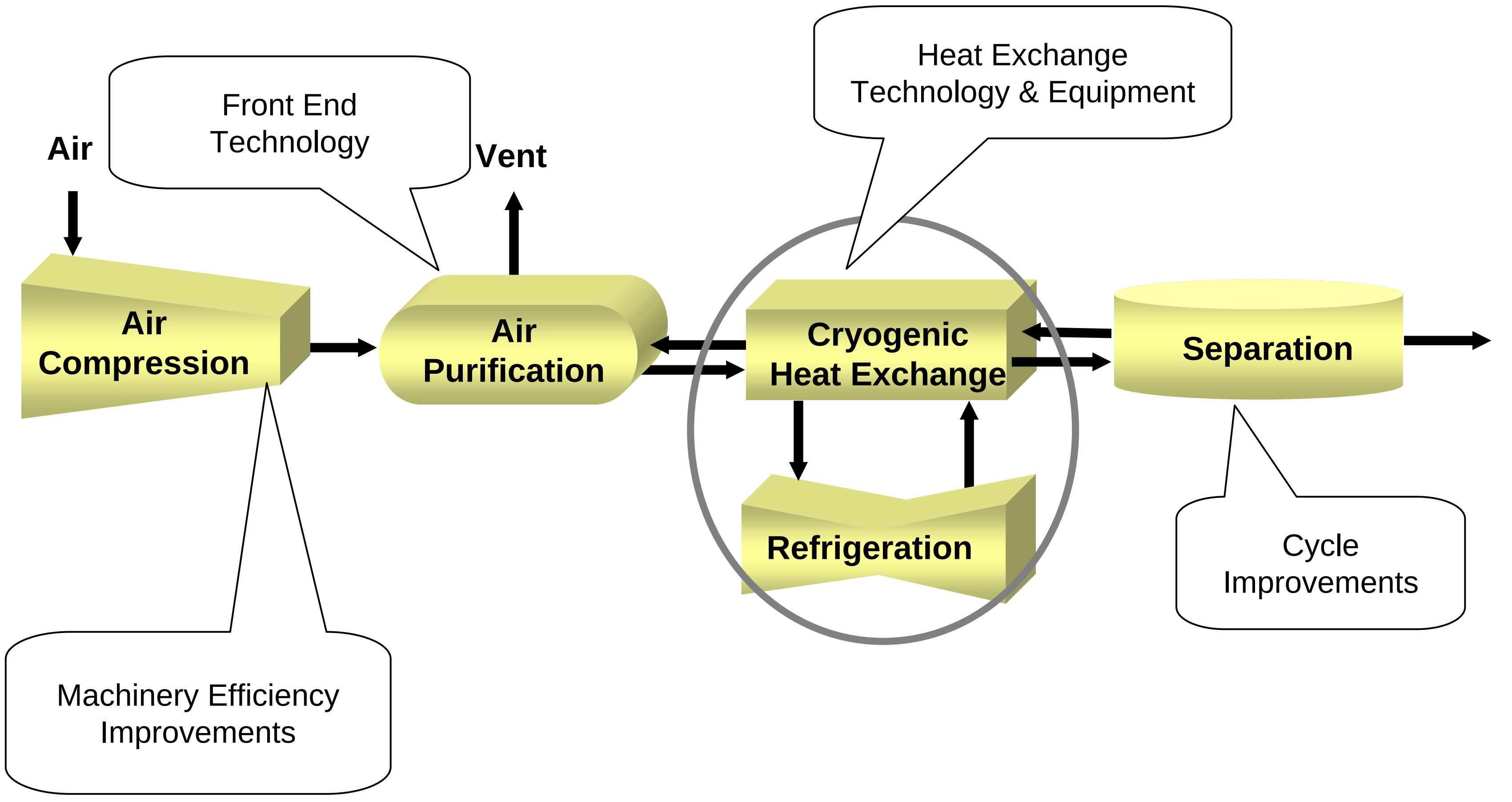
Power Costs and Design

Power is the largest component of the fully evaluated ASU cost (NPV)



Power Consumption Reduction Opportunities

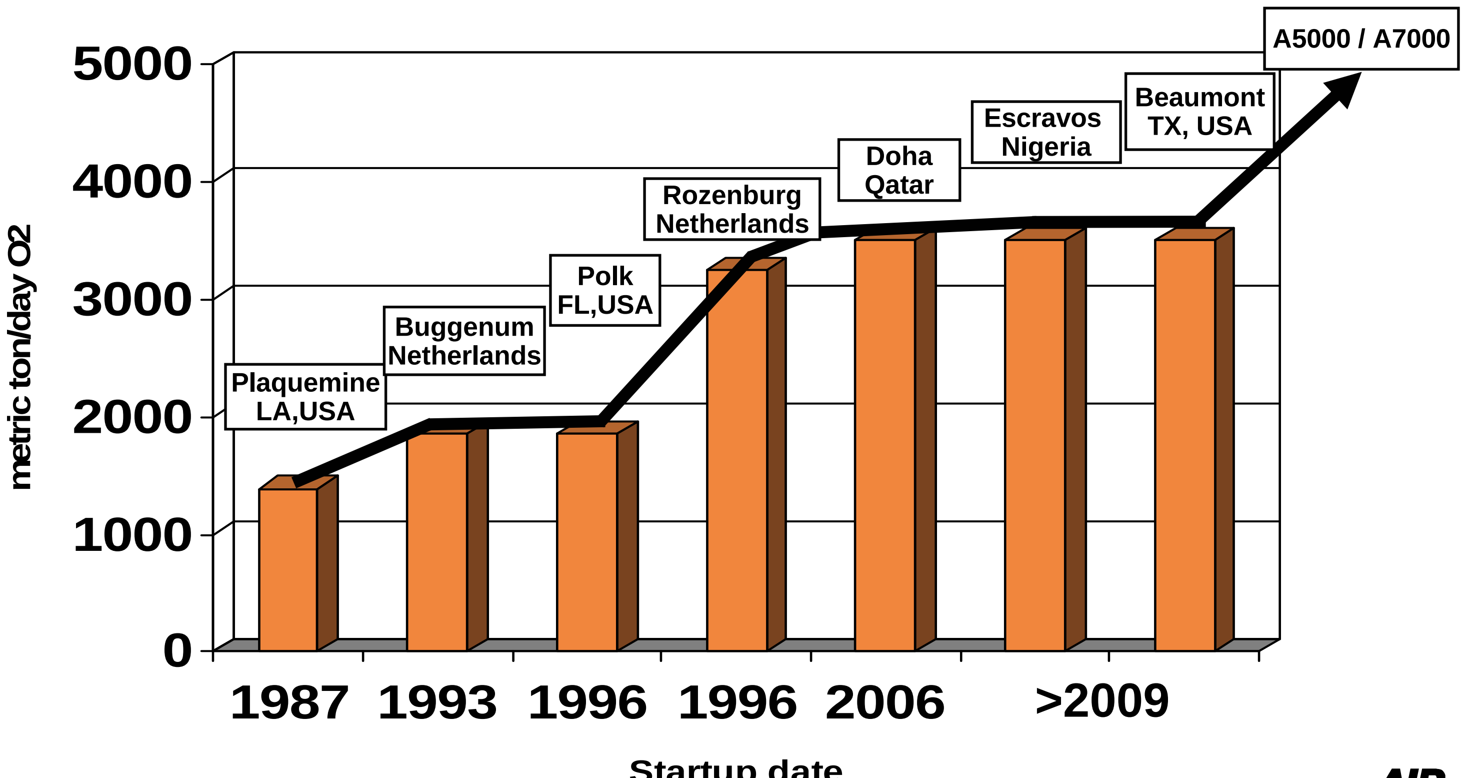
2012 Vision = 150-170 kWh/metric ton (*)



(*) 1 BAR – Gaseous Oxygen only - Depending of the relative valuation of capital and power costs

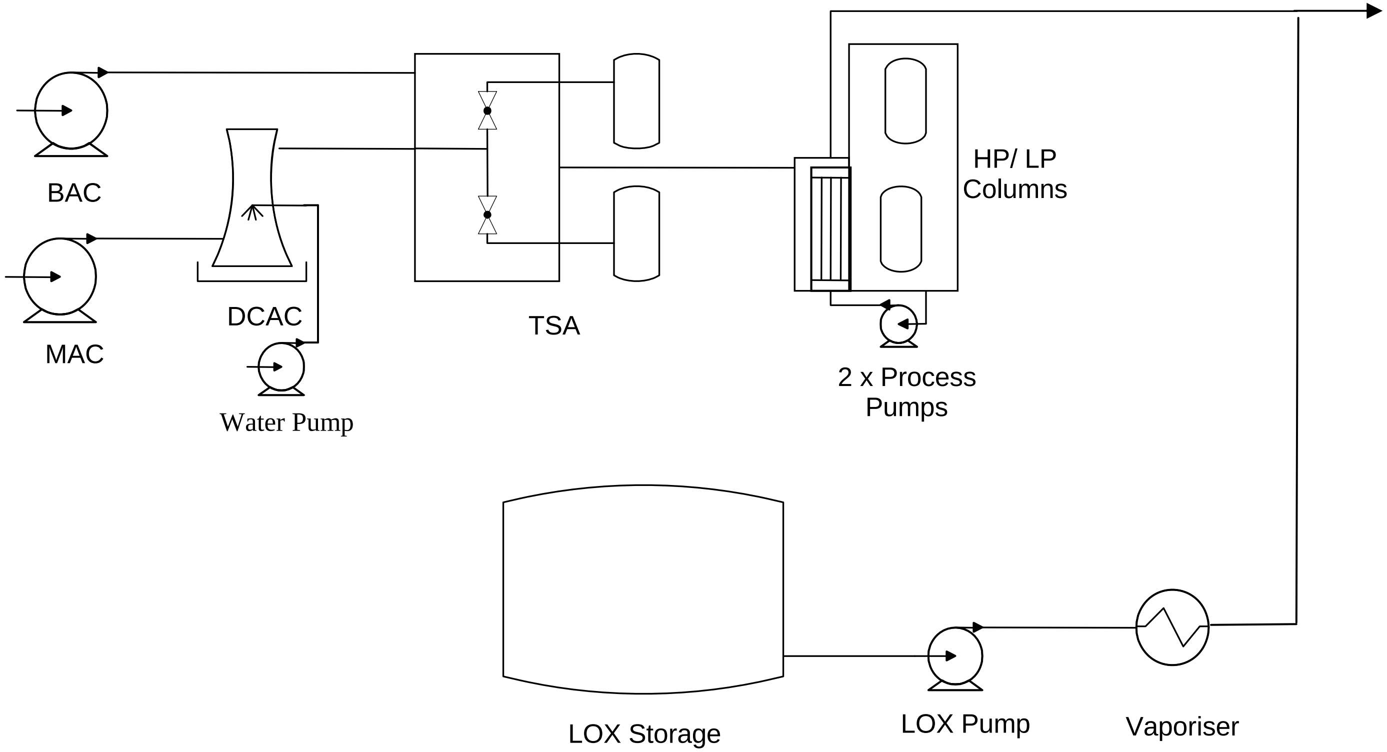
Experience - Large ASU Projects and Train Scale-up

- Market drives ASU scale-up
- Proven 70% scale-up
- Quoting 5000+ metric ton/d today

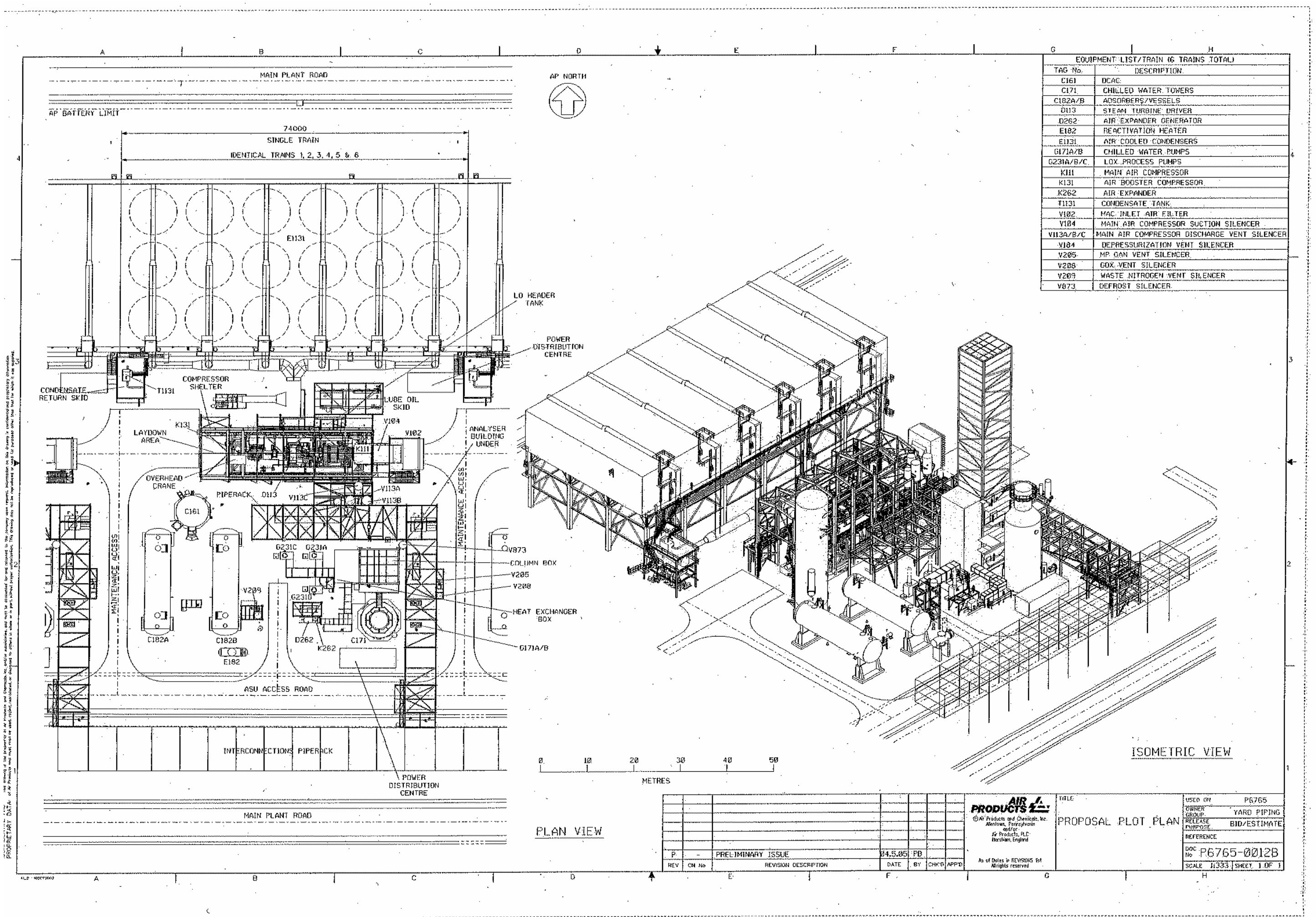


A5000

A5000 (1 train view)

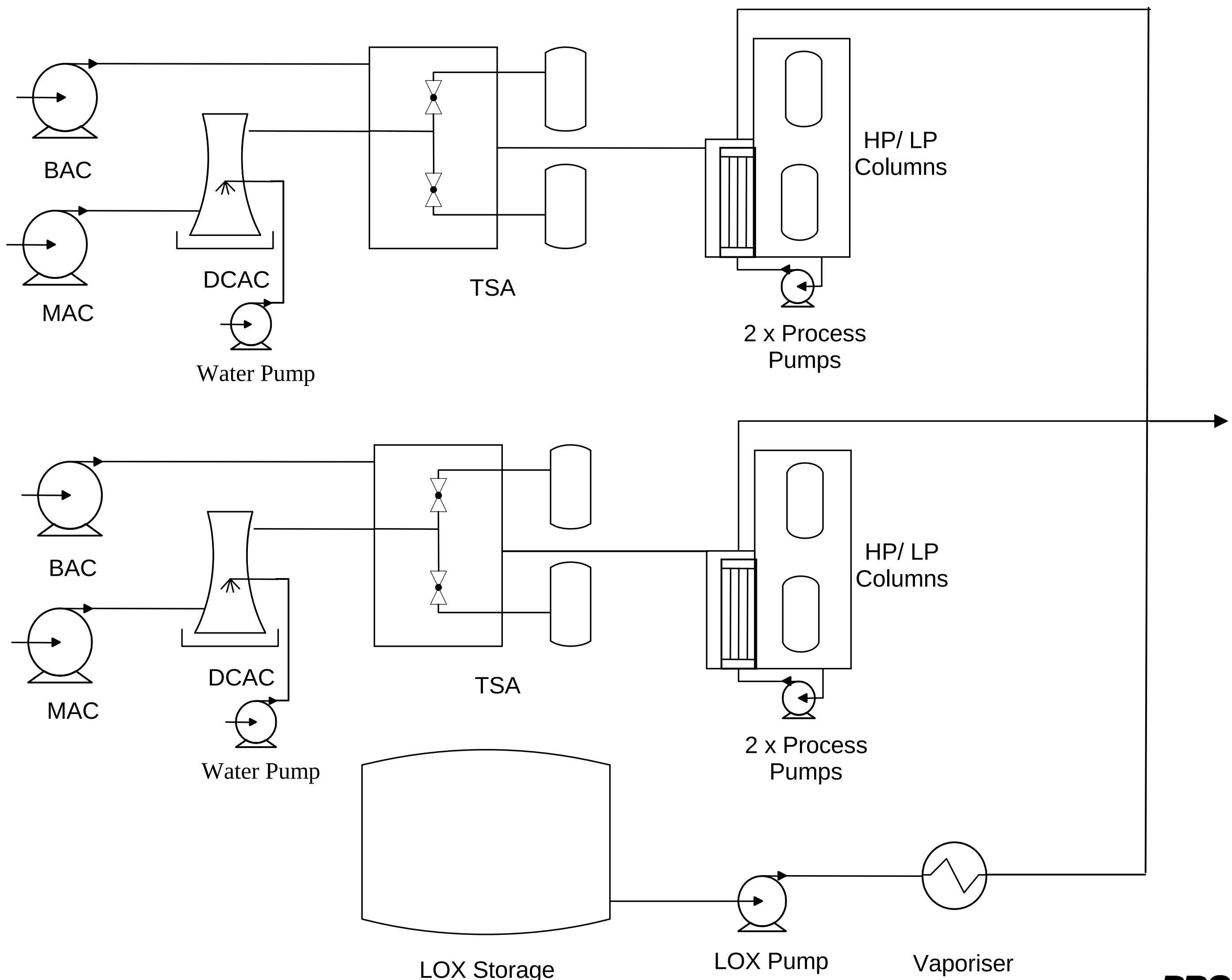


A5000 Single Train

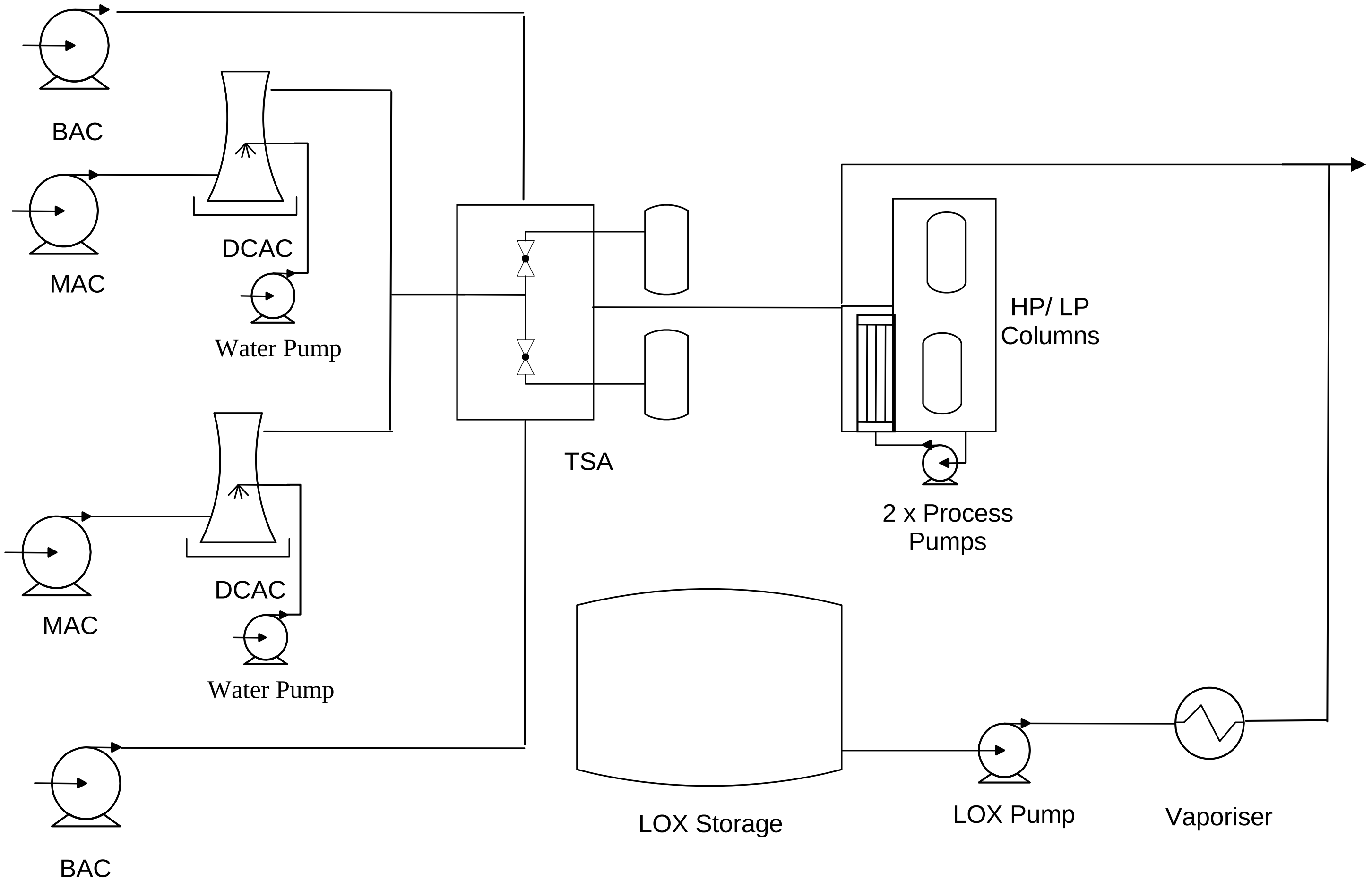


AIR PRODUCTS

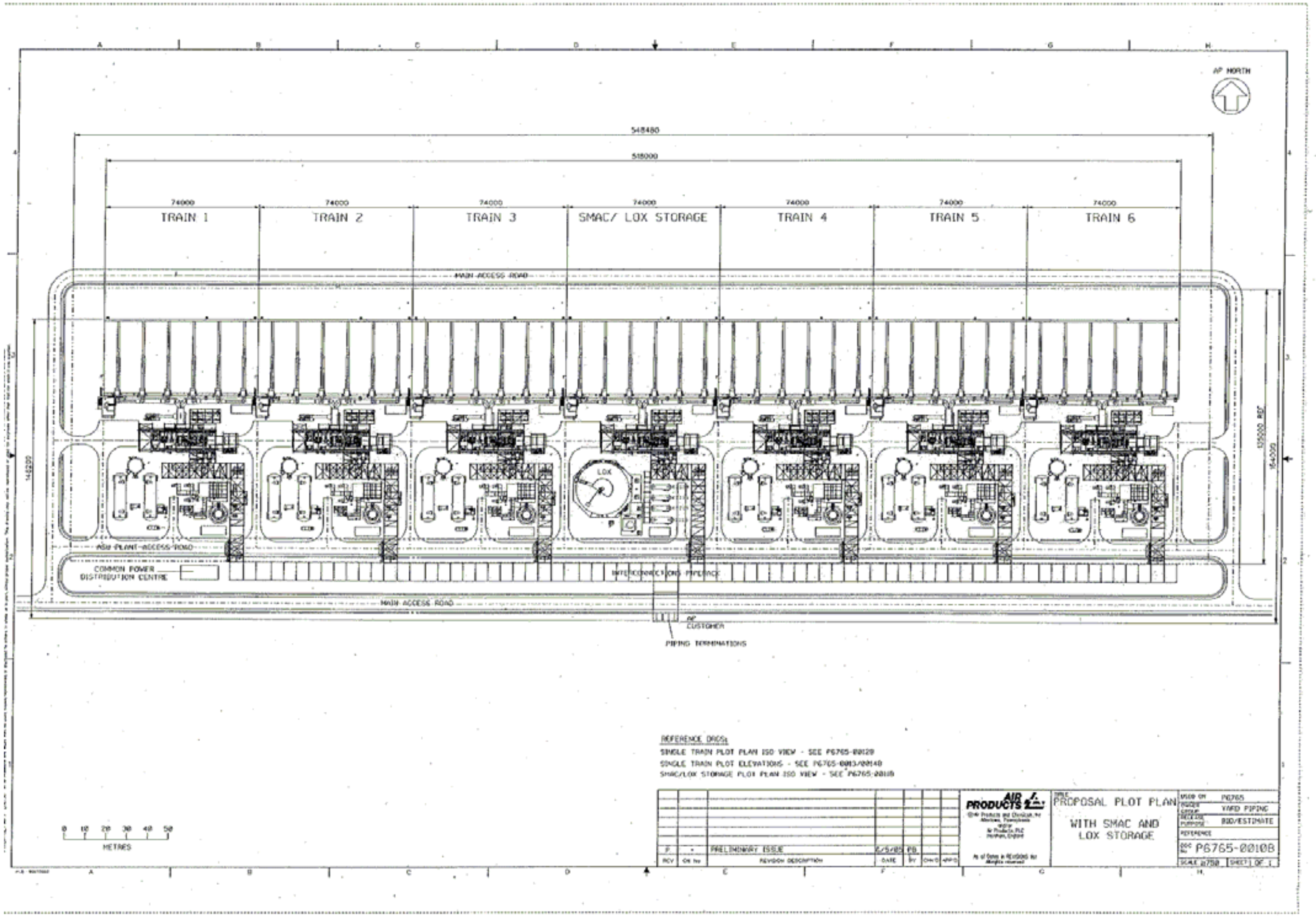
A5000 (2 x2500 trains)



A5000 (2x compression + 1 cold box view)



6xA5000 = Approx.30,000 t/d O2



Compression: Design Considerations

Oryx- Qatar – 2x3500 TPD

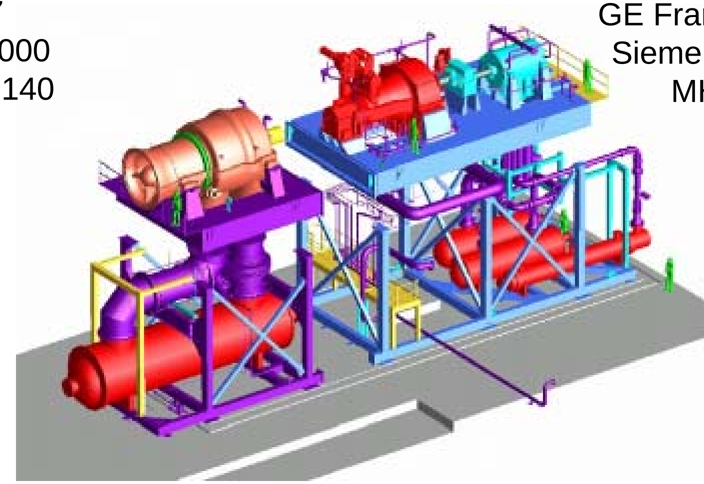
- MAC—Steam Turbine—BAC
- Air Cooled Condenser
- Shop Skids
- String Test

A5000 and A7000 t/d – Single Train Compression

- Axial main air compressor (no GT integration)
- In-line boost air and nitrogen compressors
- Four large suppliers = GE, MHI, Siemens, MAN

A5000:
GE Frame 7
Siemens STC 1000
MAN AR130-AR140
MHI M501D

A7000:
GE Frame 7 - Frame 9
Siemens STC 1300
MHI M501F



A5000 and A7000 t/d – (2x Compression –Multitrain)

- Integral gear (GT Copco or STC) or In-line air compressors (RIK)

- Integral gear or In-line boost air and nitrogen compressors (if N2 needed))

How Will Air Products Help Make Oxycoal Project A Success …

- Extensive worldwide experience building and integrating Large Scale ASU
  - Geographic diversity for R&D, Engineering, Procurement, and Manufacturing
  - A focused group of individuals to support local and project specific activities such as FEED, Build, Start-up, Operation, and Optimization
- Clear understanding of the VLASU-Oxycoal integration challenges through an active participation in the following studies:
  - IEA GHG Study on New Build Supercritical PF Coal plants – 2005
  - DTI Study on retrofitting UK Coal power plants for CO2 Capture -2006
  - DTI Study on Coal Power plants with CO2 capture for the Canadian market
  - Extensive integration experience with ASUs in other Power related projects
- Air Products is looking ahead of Cryogenic technology by developing and now in advance testing Oxygen Ion Transport Membranes (ITM)
  - Step-change savings compared to state-of-the-art cryogenic technology
    - 25-35% less capital
    - 35-60% less power
  - >65 Patents

AIR PRODUCTS

Large air separation units (ASUs)

AIR PRODUCTS

Thank you

tell me more

www.airproducts.com

AIR PRODUCTS

16:40-17:30: Discussion Forum

Oxygen production and CO_2 processing.

Focus on CO_2 processing

- Mini-panel: Presentation of two 10 minute introductions or “talking points”
  1. Regulatory barriers related to CO_2
     - C. Andy Miller, US Environmental Protection Agency, Research Triangle Park, NC 27711
  2. Technical barriers related to CO_2
     - Vince White, Air Products PLC
- Discussion
  - Floor and panel

3rd Workshop

IEAGHG International Oxy-Combustion Network
Yokohama, Japan

5th and 6th March 2008

CO_2 Quality For Storage: Technical Barriers

Vince White
Air Products PLC, UK
5th March 2008

AIR PRODUCTS

Technical Barriers???

What Technical Barriers???

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**

CO_2 PRODUCT QUALITY Generic Pipeline Spec

	Dixon Consulting EOR, Aug 2001	Kinder Morgan EOR, 2003	Industry Working Group Prelim Spec 2005	Dakota Gasification Aug 2005	Canyon Reef EOR, Dec 05	Strawman Composite
CO_2		95% min	95% min	96.80%	95% min	97% min
CH_4	<1.0%			0.30%		<1.0%
C_2H_6	<1.0%			1.0%		<1.0%
C_3+	<1.0%					<1.0%
Total HC's		5% max	5% max		5% max	<3.0%
H_2	<1.0%					<1.0%
CO			0.1% max			0.5% max
N_2	<2.0 N_2 & H_2	4% max	4% max		4% max	1-3% max TBD
Other Inerts						
Total Inerts						<3%
O_2	<2.0 ppmw	10ppm	100 ppmv max		10 ppmv max	2 ppmv
H_2S	<100 ppmw	10-200 ppm	10-200 ppmv max	1.10%	1,500 ppmv max	10-200 ppmv TBD
SO_2	<5.0 ppmw					5 ppmv
Total Sulfur	<300 ppw				1,450 ppmv max	10-200 ppmv
H_20	<-5C DP @ 300 psia	30 lbs/MMCF max	<-40C DP	Bone dry	28 lbs/MMCF max	<1 ppv
Hg			Controlled			TBD
Other				0.90%		TBD
Glycol		0.3 gal/MMCF max	0.174 m3/MMm3		0.3 gal/MMCF max	TBD
Methanol						TBD
Selexol						TBD
Amine						TBD
Delivery Pressure			2,000 psia	2,190 psia		2,200 psig
Temperature		120F max	120F max	(2,700 psig @ source)	120F max	120F max

Dynamis CO_2 quality recommendation

Compound	Concentration limit	Remarks
H_2S	200 ppm	Health and safety considerations
CO	2000 ppm	Health and safety considerations
SO_x	100 ppm	Health and safety considerations
NO_x	100 ppm	Health and safety considerations
H_2O	500 ppm	Technical limit
O_2	Aquifer <4 vol% (all non cond. gases), EOR >100 ppm	Technical limit; storage issue
CH_4	Aquifer < 4 vol%, EOR <2 vol% (all non cond. gases)	Like ENCAP
N_2, Ar, H_2	<4 vol% (all non cond. gases)	Like ENCAP
CO_2	> 95%	Result of other compounds in CO_2

Dynamis

FUNDED BY THE EUROPEAN UNION

SIXTH FRAMEWORK PROGRAMME

http://www.cachetco2.eu/c2ws/presentations/39_dynamis_de_visser.pdf

AIR PRODUCTS

Why Remove Inerts?

- More volume
  - Makes pipes bigger/reduced capacity
  - Takes up storage space
- Avoids two phase flow
- Requires less compression power

How to do it?

- SOx, NOx, Hg
  - Conventional Technologies
  - Air Products' integrated CO_2 purification system
- Water
  - Glycol, Adsorption
- Inerts
  - Low temperature phase separation
- Oxygen
  - Low temperature distillation
  - Catalytic combustion?

Thank you

Vattenfall's Schwarze Pumpe Oxyfuel Pilot – An update

Marie Anheden
Vattenfall Research and Development

3rd IEA GHG Oxyfuel Workshop March 5-6, Yokohama, Japan

VATTENFALL

Vattenfall 30 MW Oxyfuel pilot plant

- Vattenfall has taken a decision to build a 30 MW_{th} Oxyfuel PF pilot plant
- New-built plant located next to the Schwarze Pumpe power station in Germany
- Investment decision taken by Vattenfall in May 2005. In operation August 2008.
- Size of pilot plant chosen to facilitate a scale-up to a commercial-size burner as the next step

VATTENFALL

Objectives of the tests

Pilot testing will result in validation and tuning of the more or less commercially available technologies included in the Oxyfuel concept to allow launch of a demonstration project of the technology in commercial scale within 5 years.

⇒ Define optimal operating conditions for Oxyfuel conditions in a large-scale facility for the entire process. Experience will serve as data input for scale-up of the Oxyfuel concept.

⇒ Identify critical issues for further R&D

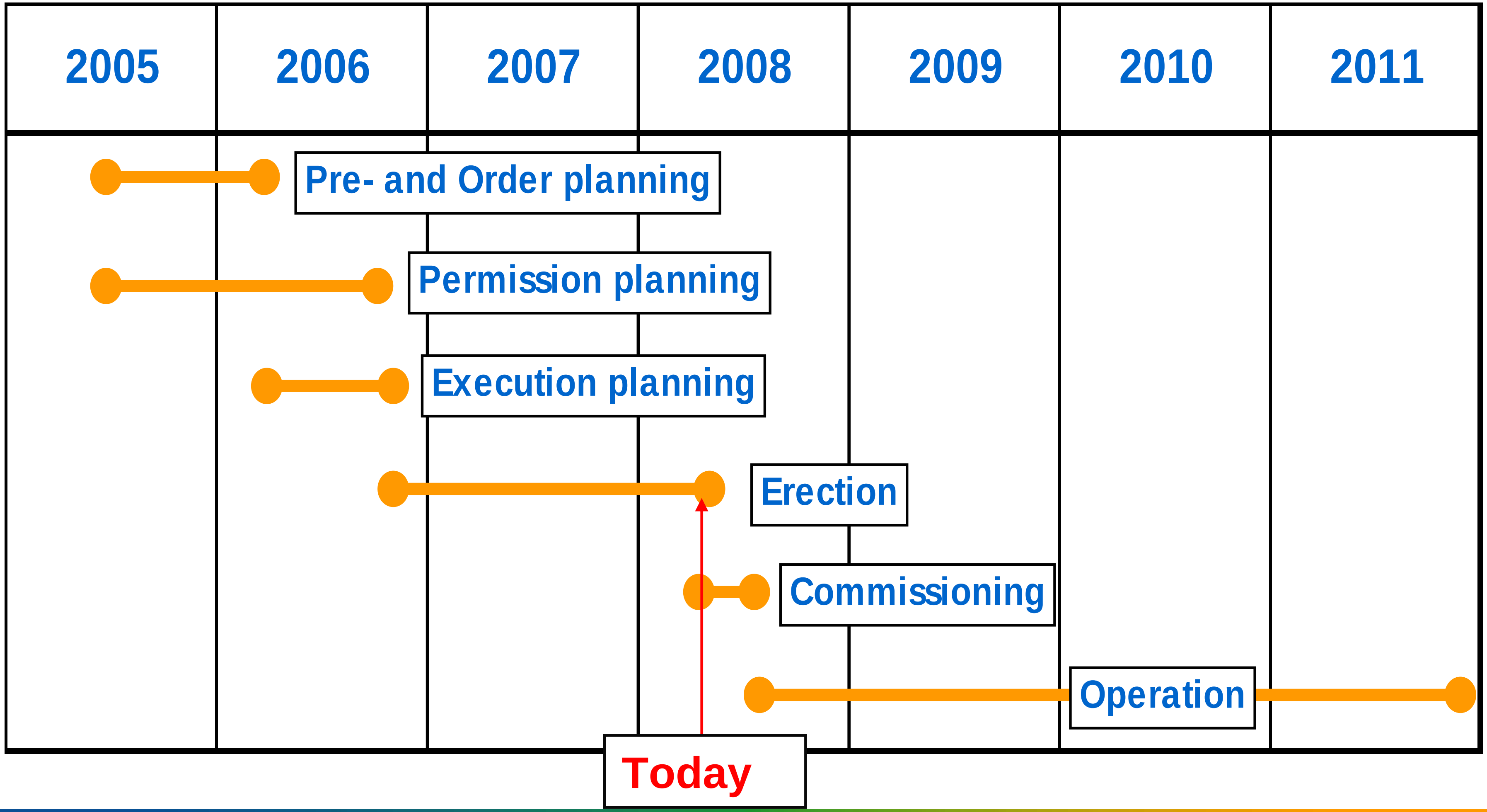
⇒ Gain operating experience in the Oxyfuel field

VATTENFALL

Basic data

Boiler: Pulverized fuel	Combustion heat performance Steam production Steam parameter	30 MW_{th} 40 t/h 25 bar / 350 °C
Coal: pulverized lignite (Lausitz)	LHV Moisture Coal demand	21.000 kJ/kg 10,5 % 5,2 t/h
Media:	Oxygen (purity > 95%) Own consumption CO_2 (liquid)	8,5 t/h 8,5 MW 9 t/h
Other:	Required area Erecting time Investment	14.500 m² 15 month 70 Mio. €

Overall Time schedule



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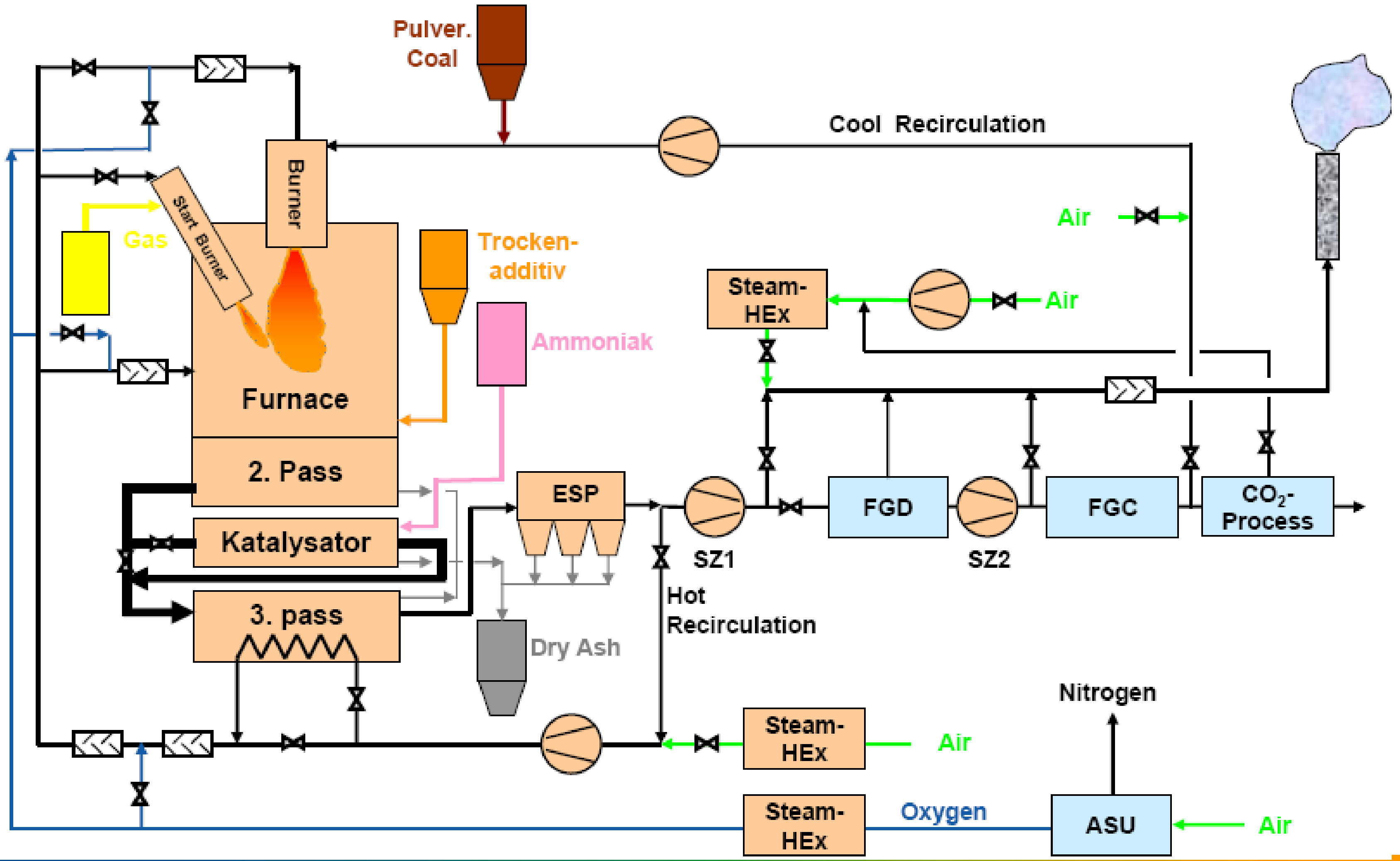
Process scheme of the pilot plant



VATTENFALL

The plant – status 2008-01-15

Main Contractors

General planer VATTENFALL
VATTENFALL EUROPE PowerConsult GmbH

ALSTOM
Boiler / ESP

Linde
ASU / CO_2-plant

Babcock Borsig Service Group
FGD

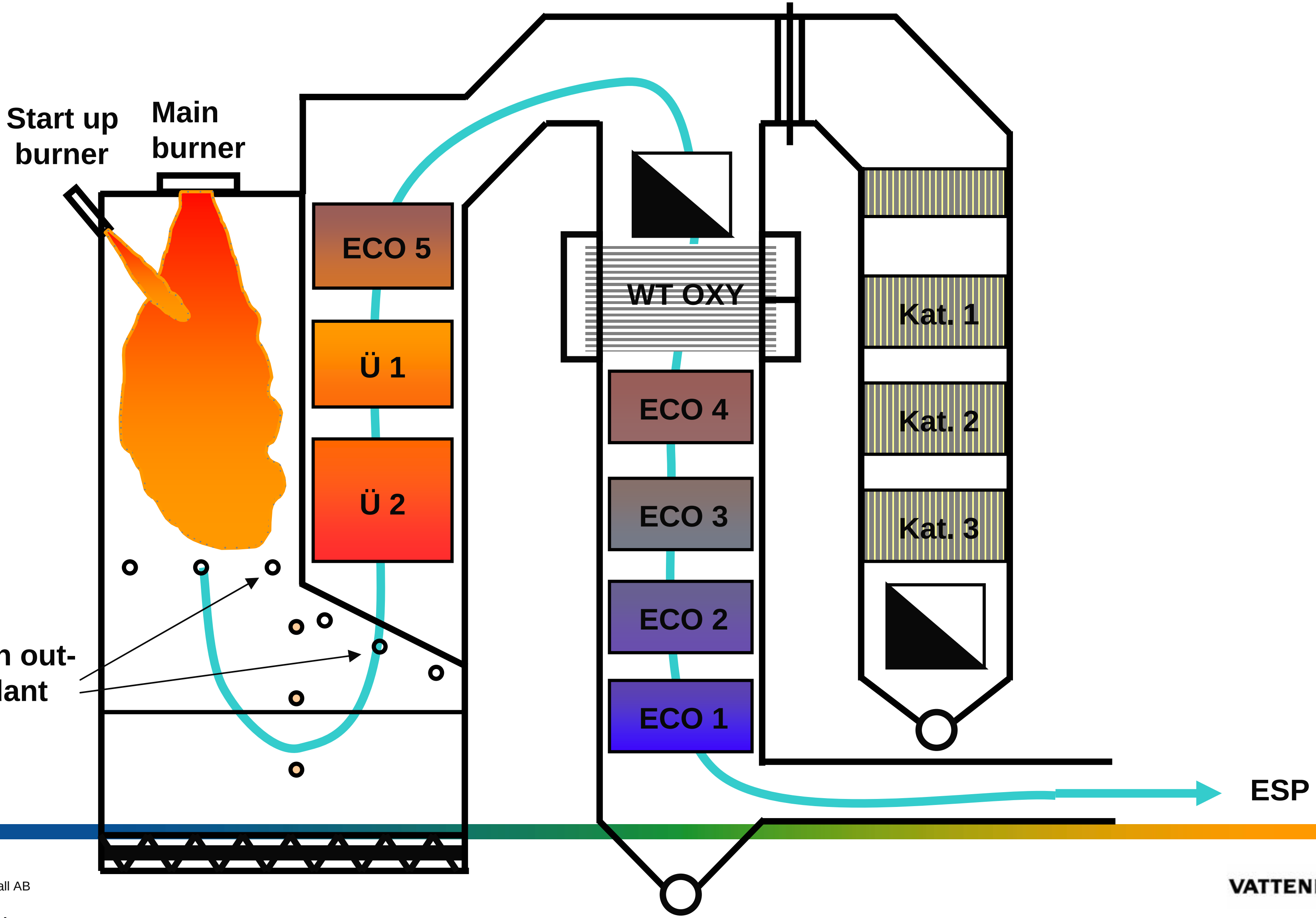
SIEMENS
EMIS ELECTRICS
I&C system

TREMA®
FGC

OBAG
Ostsächsische Baugesellschaft mbH
Civil

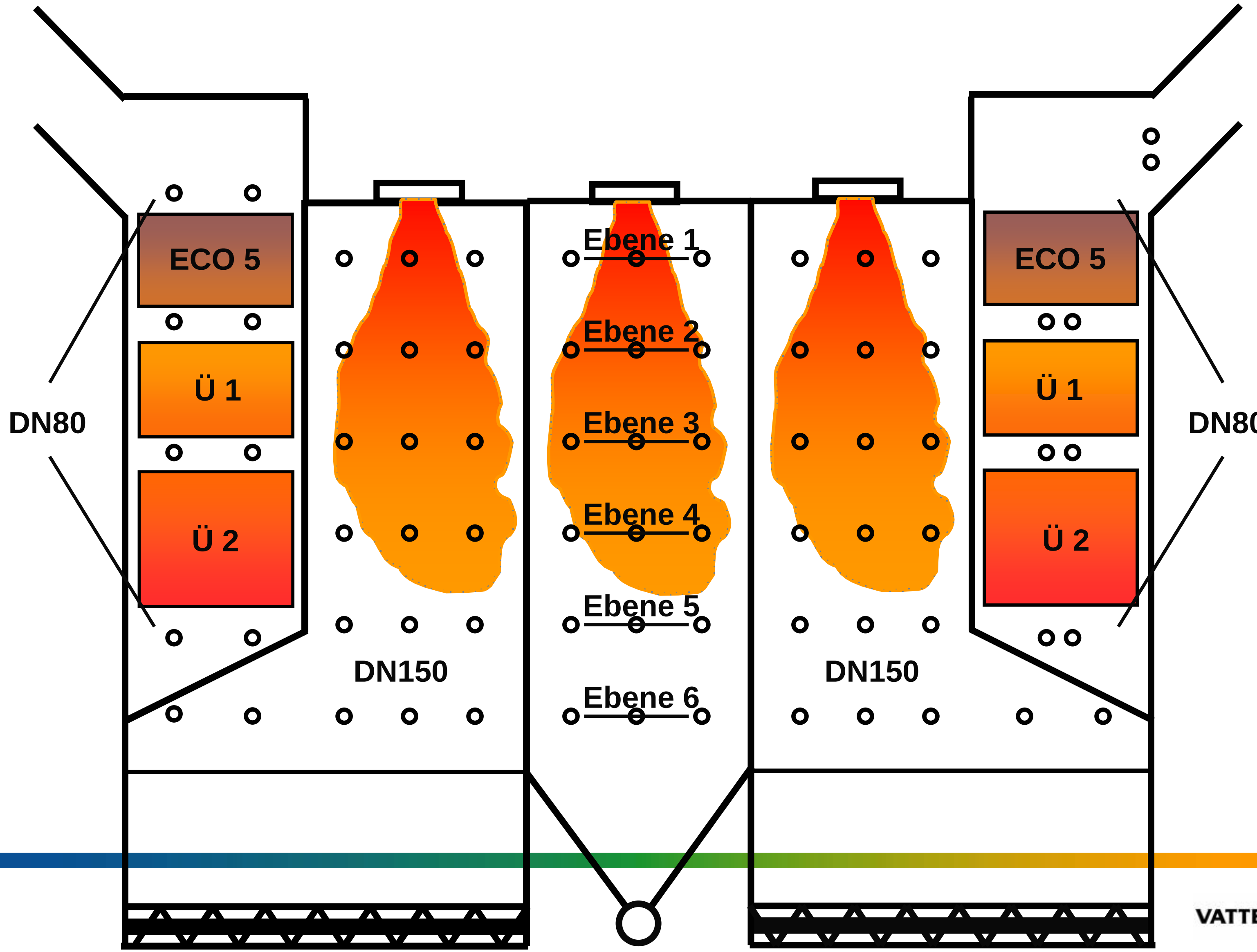
ESP   Boiler steel structure   and equipment

The Oxyfuel boiler in cross section (3 passes)



VATTENFALL

Measurement ports in the furnace and 2nd pass



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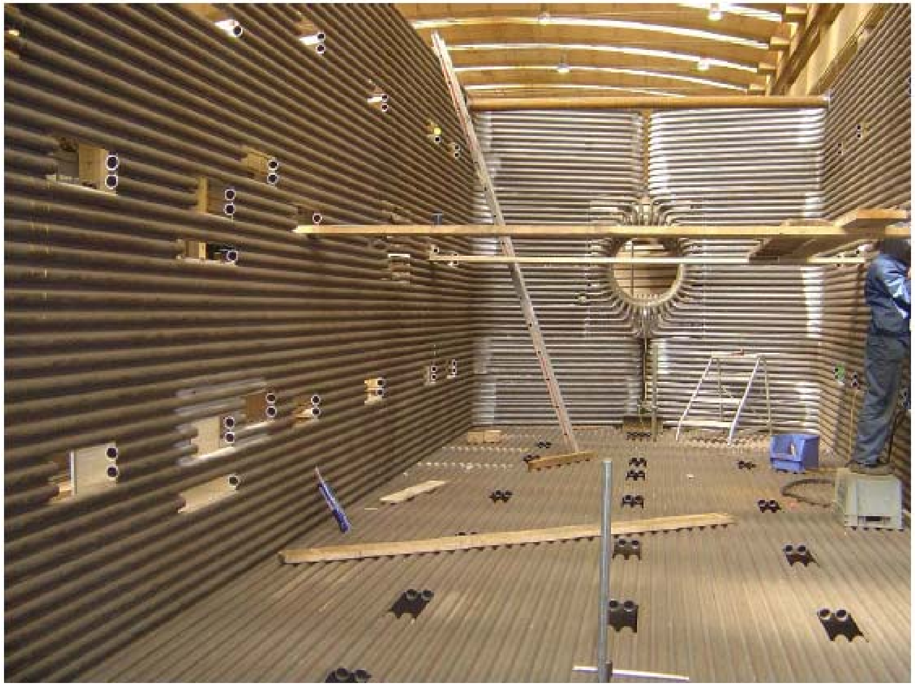
The furnace in the making



Measurement ports in the furnace

O2-tank, ASU

VATTENFALL

Flue gas desulpherisation

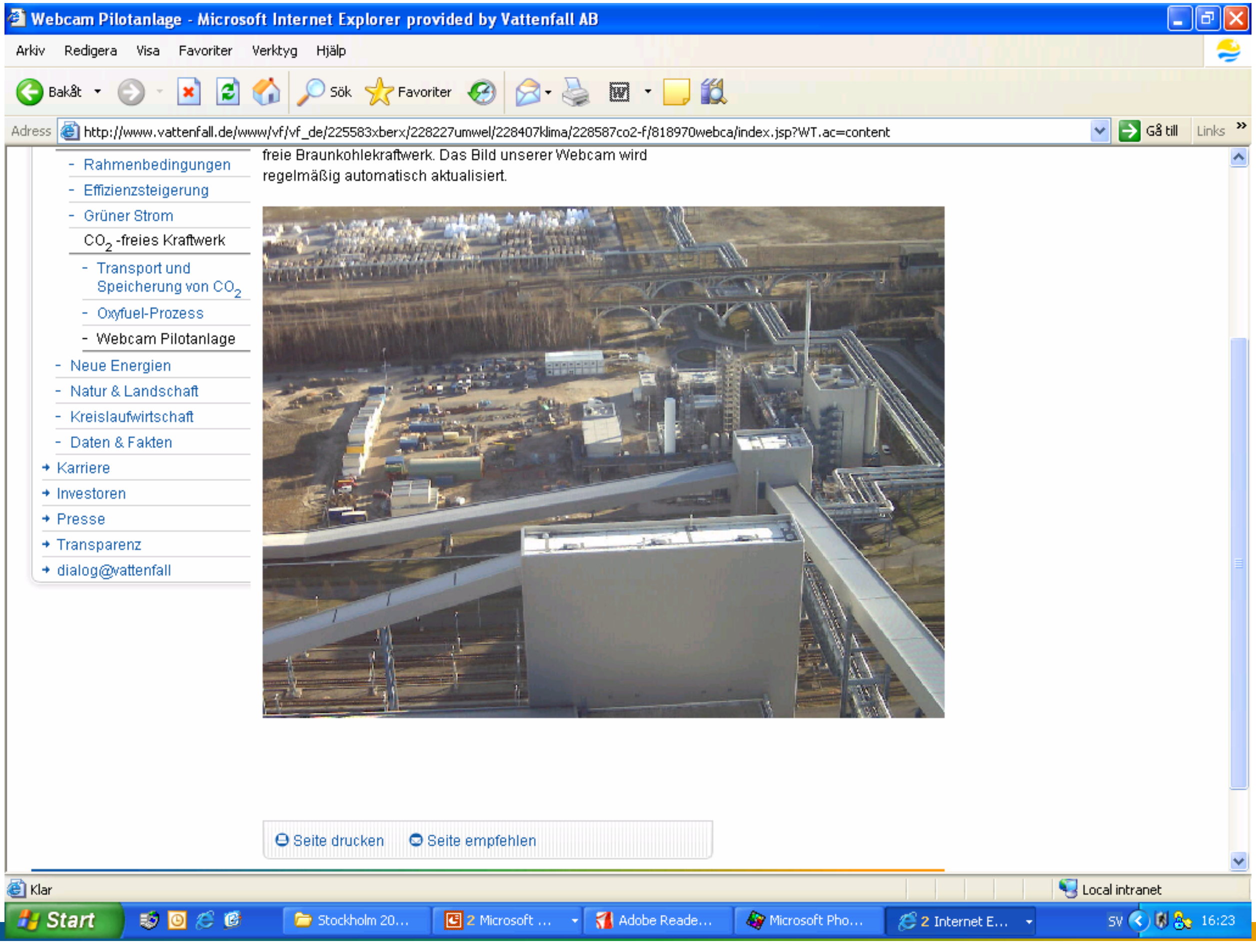
Flue gas condenser

Compression chiller & CO2 tank station

VATTENFALL

Pilot plant web camera

http://www.vattenfall.de/www/vf/vf_de/225583xberx/228227umwel/228407klima/228587co2-f/818970webca/index.jsp?WT.ac=content



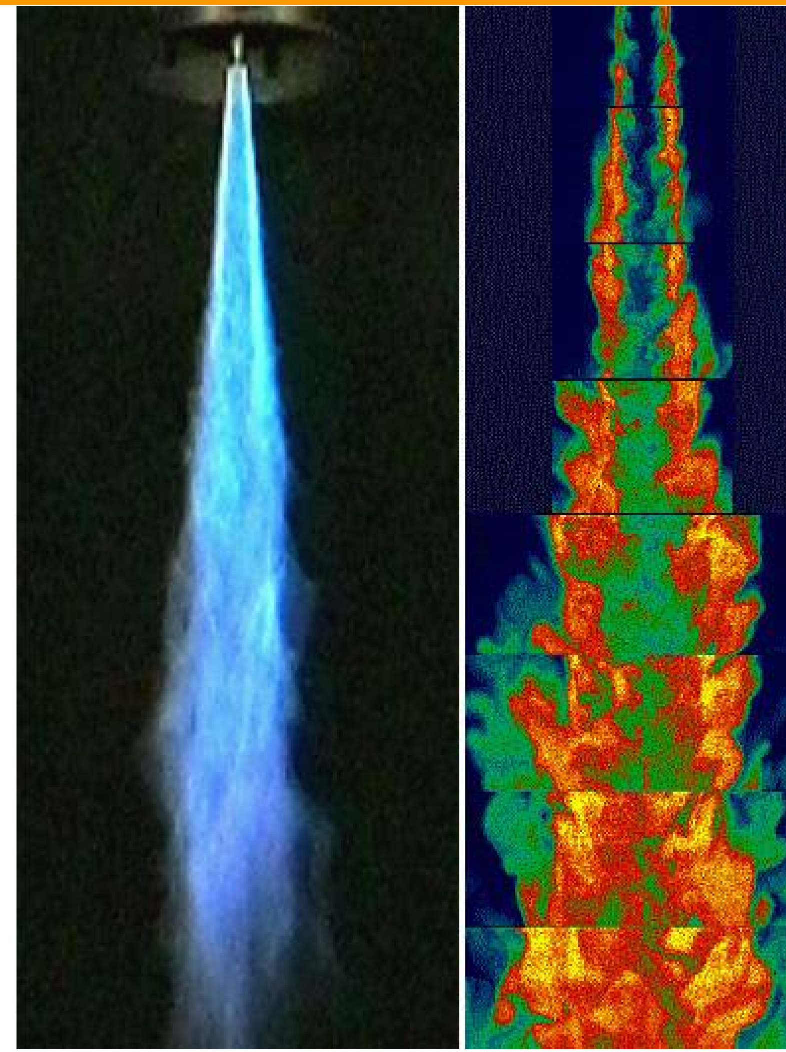
Test Program for the Oxyfuel Pilot Plant

Boiler tests:

- Tests with lignite (1st test period) and hard coal
- Variation of moisture content in lignite (10.5 – 20 %)
- Variation of oxygen excess (1 – 5 %)
- Variation of recirculation (flow, temperature, O_2-content)
- Variation of oxygen content at different burner registers

Benchmark against air-firing:

- Combustion performance
- Ash qualities
- Flue gas composition
- Heat transfer
- Combustion characteristics
- Flame characteristics
- Corrosion potential
- Identification of optimal configurations



VATTENFALL

Test Program for the Oxyfuel Pilot Plant (2)

Tests of other components:

- Interaction between ASU and boiler (load change)
- Separation rates of ESP, FGD and FGC at different flue gas compositions
- Reachable raw gas qualities upstream of CO_2-processing
- Scrubbing efficiency of CO_2-processing
- CO_2-recovery rate of entire process (target > 90 %)

Benchmark:

- Requirements on process control / I&C
- ideal pH-value for FGD/FGC process
- Corrosion potential
- Minimum requirements for raw gas quality upstream of CO_2-processing
- Identification of optimal operating conditions

VATTENFALL

Pilot CO_2 storage project in the Altmark gas field

OIL&GAS JOURNAL

GDF, Vattenfall plan CO2 pilot program in Germany

Doris Leblond *OGJ Correspondent*

PARIS, Sept. 28 -- In a move it claims is consistent with its sustainable development policy, Gaz de France has signed a cooperation agreement with Germany's Vattenfall Group for a carbon dioxide pilot project in Germany.

Erdgas Erdol GMBH Berlin, GDF's wholly owned exploration and production affiliate, will use CO2 to enhance gas recovery from its nearly depleted Altmark gas field—the second largest onshore field in Europe.

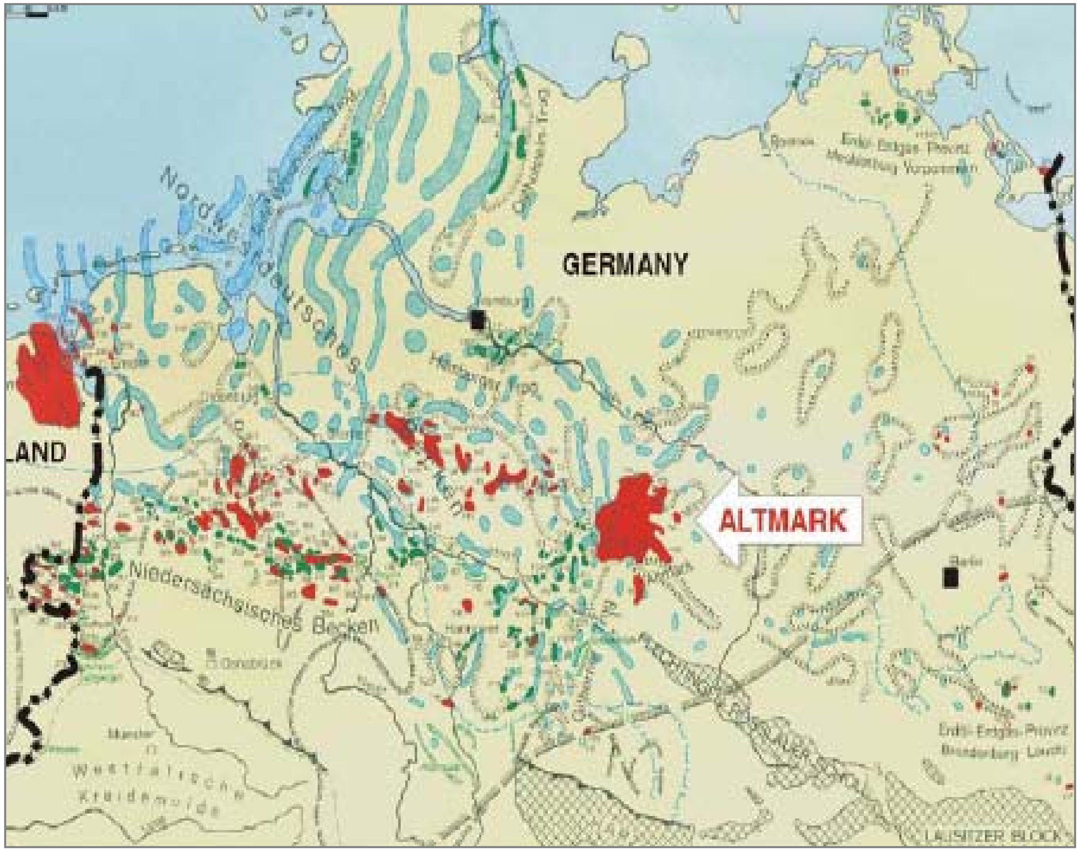
The project will take 15 months to implement and will contribute to GDF's research program on CO2 capture, injection, and storage.

VATTENFALL

Altmark gas field

Altmark:

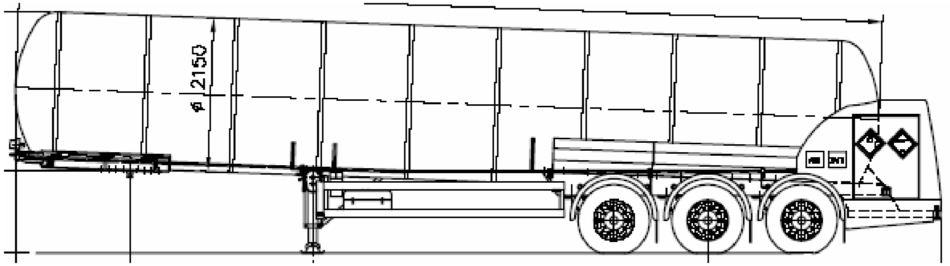
- One of Europe's largest on-shore natural gas fields
- Gas findings at 3000 m depth
- Natural gas production since 1969
- 78% recovery rate
- The field is now at the end of its economic life
- Methods for life time extension is being investigated
- The R&D-project CSEGR has shown that it seems possible to extend the life time through CO_2 injection
- A 3 year pilot trial period will be initiated using CO_2 from Vattenfall's Schwarze Pumpe oxyfuel pilot



VATTENFALL

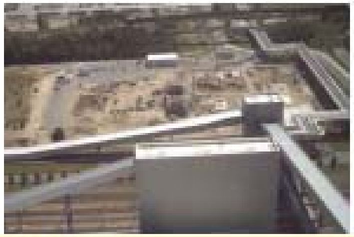
Altmark – Schwarze Pumpe

- Estmated storage capacity 600 Mton
- Total planned injection: ca. 100.000 ton CO_2
  → 0,02% of the storage capacity
- Truck transport will be used for the transportation of CO_2 from the Schwarze Pumpe pilot to Altmark
  - 7-8 Trucks in continuous operation
- If the pilot trial shows that Altmark is suitable for large scale operation it will be used for a demo plant:
  - CO_2-capture from a demo plant ~ year 2015 → 1,5-2 Mton per year
  - Pipeline transport 330 km
  - A route could be arranged along the existing natural gas pipeline



Pilot- och Demonstration projects in perspective

10 years of R&D is now resulting in investments in several large-scale projects:



Plant	Schwarze Pumpe, Germany	Mongstad, Norway	Demoplants, Germany, Denmark, Poland
Type	Large scale pilot plant	Large scale pilot plant	Demonstration plant
Capacity		100 000 ton CO_2/a (~35 MW)	
Fuel	al	Flue gas from CCGT & cracker	
CO_2 technology		Post-combustion	
Operation	2008	2010	Ca 2015

Storage Pilot by GdF / Vattenfall

Storage demonstrations by Vattenfall / Cooperation partners

Thank you!

APP Oxyfuel Working Group (OFWG)

3rd Oxy-Combustion Network, Yokohama, March, 2008

Background

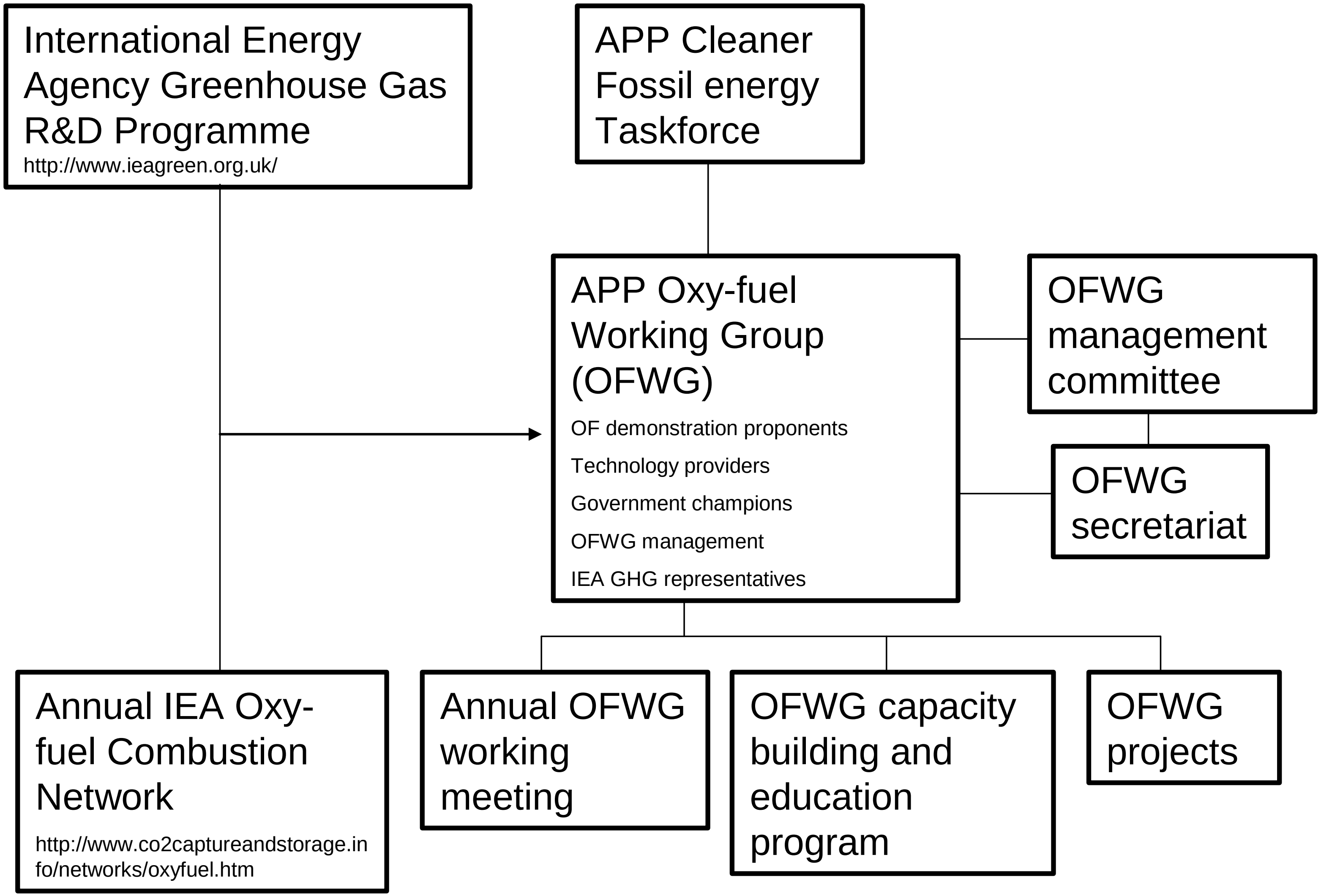
- Oxyfuel technology has a number of “demonstration “ projects
- The demonstrations have common issues, which can be progressed by collaboration
- OFWG will not restrict its activities to APP countries alone

OFWG objective and participation

- The objective is to facilitate and support the implementation of oxy-fuel demonstration trials, and thereby accelerate deployment of the technology.

- OFWG participation is for proponents and technology suppliers of oxyfuel demonstrations and large pilot-plants.

OFWG – IEA Oxyfuel Network relationship



Inaugural meeting objectives

- To explain and develop the objectives of the OFWG
- Establish interest in participation
- Establish areas of research projects in which participants are willing to work collaboratively, and planning of initial projects
- Plan first education course and future OFWG meetings

OFWG support from APP

- Meetings and management – OFWG and education course
- Web site
- Some support for project development
- Roadmap and updates

  - For an initial three year period

The demonstrations

Demo/pilot-plant	Paper to be presented at 3rd Oxyfuel Network	Project leader	Technology provider(s), nominated by PLs
Vattenfall pilot plant	Vattenfall Schwarze Pumpe Pilot Plant, Germany	***Prof Lars Strömberg, Vattenfall***	?
Callide	Callide Oxyfuel Project – C. Spero, T. Yamada, E. Sturm, and D. McGregor CS Energy, Australia	***Dr Chris Spero, CS Energy***	***Toshihiko Yamada, IHI***
TOTAL	The TOTAL CO2 Pilot at Lacq N. Aimard, and C. Prebende TOTAL, France	***Dr Nicolas Aimard or Claude Prebende, TOTAL***	?, Air Liquide
CIUDEN	Test Facilities for Advanced Technologies for CO2 Abatement and Capture, Vicente J. Cortés CIUDEN, Fundacion Estatal Ciudad de la Energia, Spain	***Prof Dr. Vicente J. Cortés, CIUDEN***	***Mr. Arto Hotta, Foster Wheeler***
Youngdong	Oxy-Combustion Research Activities in S. Korea – Overview to the Youngdong 100MWe Oxy-Combustion Power Station Project Development J. S. Kim, KIST, Korea	***Dr D C KIM, KEPRI*** ***Dr Jong Soo KIM,KIST***	Not represented, as yet to be decided
Jamestown/Praxair	Oxy-Coal Combustion Demonstration Project D. Bonaquist, R. Victor, M. Shah, H. Hack, A. Hotta, D. Leathers Praxair, USA; Foster Wheeler, USA/Finland; and Jamestown Board of Public Utilities	***Dan Bonaquist, Praxair***	***Horst Hack, Foster Wheeler***
Orville Project	Jupiter Oxygen -15 MWt Oxy-Combustion Boiler Test Results B Patrick, Jupiter Oxygen	***Brian Patrick, Jupiter Oxygen***	***Gerry Hesselman, DOOSAN Babcock***
Babcock&Wilcox pilot plant	Scale Up of Oxy-Coal Combustion at B&W's 30 MWt CEDF H Farzan, B&W	***Kevin McCauley, B&W***	?, Air Liquide
Saskpower		Not attending	?

OFWG Inaugural Meeting aims, Tuesday, March 4th

- Understanding of project
- Interest in participation
- Potential project areas, and action points
- Education course

OFWG Inaugural Meeting outcomes

- **Roadmap for technology deployment, with IEA GHG?**
  - Technology status. Issues delaying deployment. Path to commercialization

- **Possible – collaborative - OFWG project areas**
  - ***Regulations.*** CO_2 quality for geological storage. Stack (flue gas) emissions during operation – ppm or gm/MJ.Emissions from compression operations
  - ***Plant specification guidelines***. Plant design. Operation
  - ***Safety.*** Materials for high O_2 environments.Higher O_2 streams safety requirements, >23%O_2. Explosions less possibility with O_2/CO_2 than O_2/N_2.O_2 injection into ash streams with ash containing unburnts
  - ***Coal quality tolerance.*** Sulfur, ash, moisture

- **Education course, annually**

Closing comments

- A good start!!
- Oxyfuel demonstrations are being developed, several starting in 2008-10
  - Of similar scales
- Some OFWG projects identified for common pre-competitive projects

CO_2 Capture Ready Plants

John Davison
IEA Greenhouse Gas R&D Programme

3rd Oxy-combustion Network Meeting
Yokohama, Japan, 5th-6th March 2008

Overview

- The need for capture ready plants
- Definition of capture ready
- Technical requirements
- Economic considerations
- Which technologies are best for capture ready?

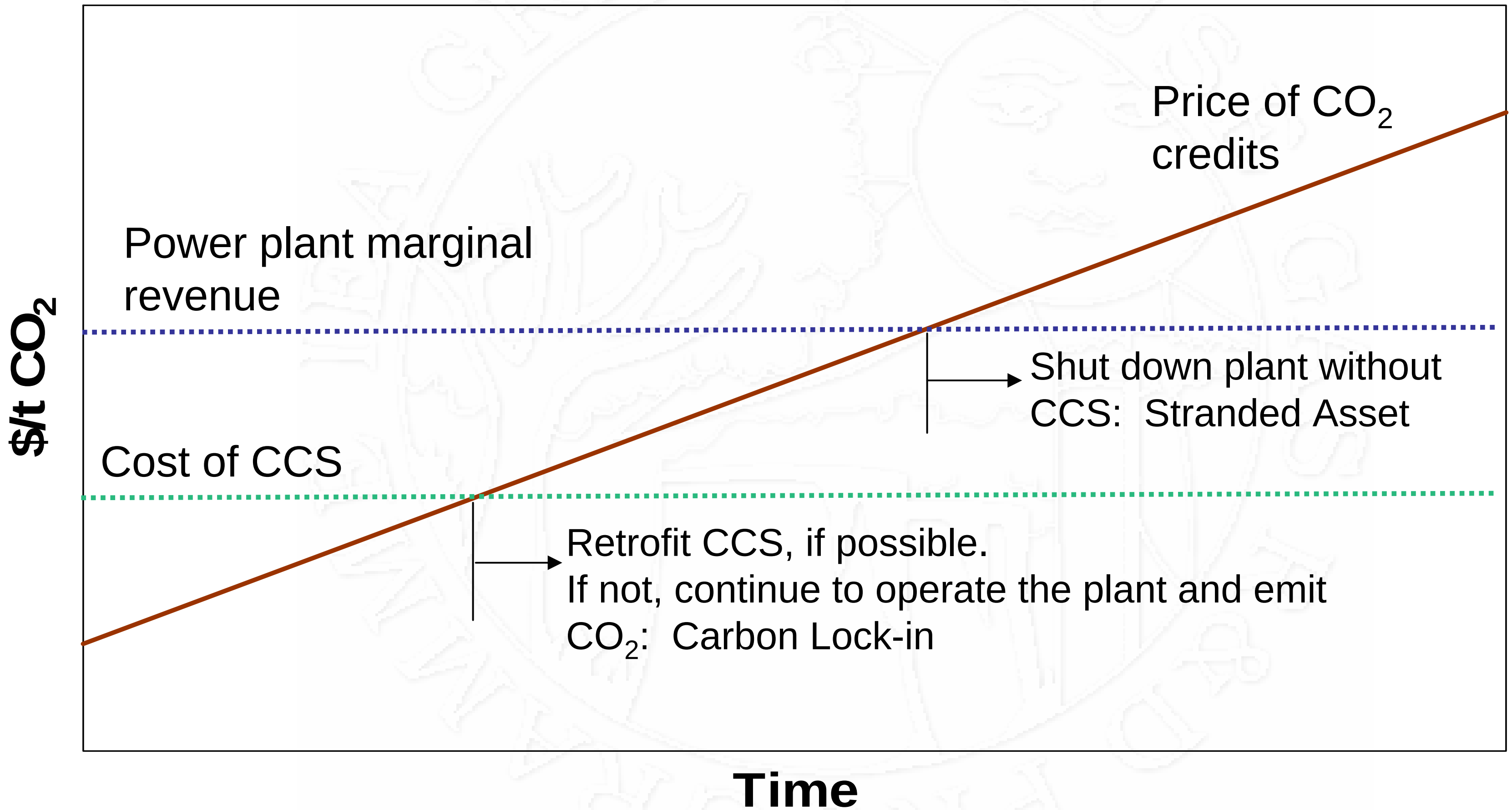
Why are Capture Ready Plants Needed?

- CCS is currently not economic in most cases
  - No economic incentives in many countries
  - Even where there are incentives they are usually too low and uncertain
- CCS is still at the development and demonstration stage
  - Demonstration plants are needed to improve investor confidence
  - Regulatory issues are being addressed
- There is a large demand for new power stations in the near future
  - Developing countries – mainly new capacity
  - Developed countries – mainly replacement capacity
- Power plants have long lives (>50 years)
  - Emission reductions are likely to be necessary during their lifetimes

What is meant by 'Capture Ready'

- A CO_2 capture-ready power plant is a plant which can include CO_2 capture when the necessary regulatory or economic drivers are in place.
- The aim of building plants that are capture-ready is to reduce the risk of 'carbon lock-in' or 'stranded assets'.

Carbon Lock-in and Stranded Assets



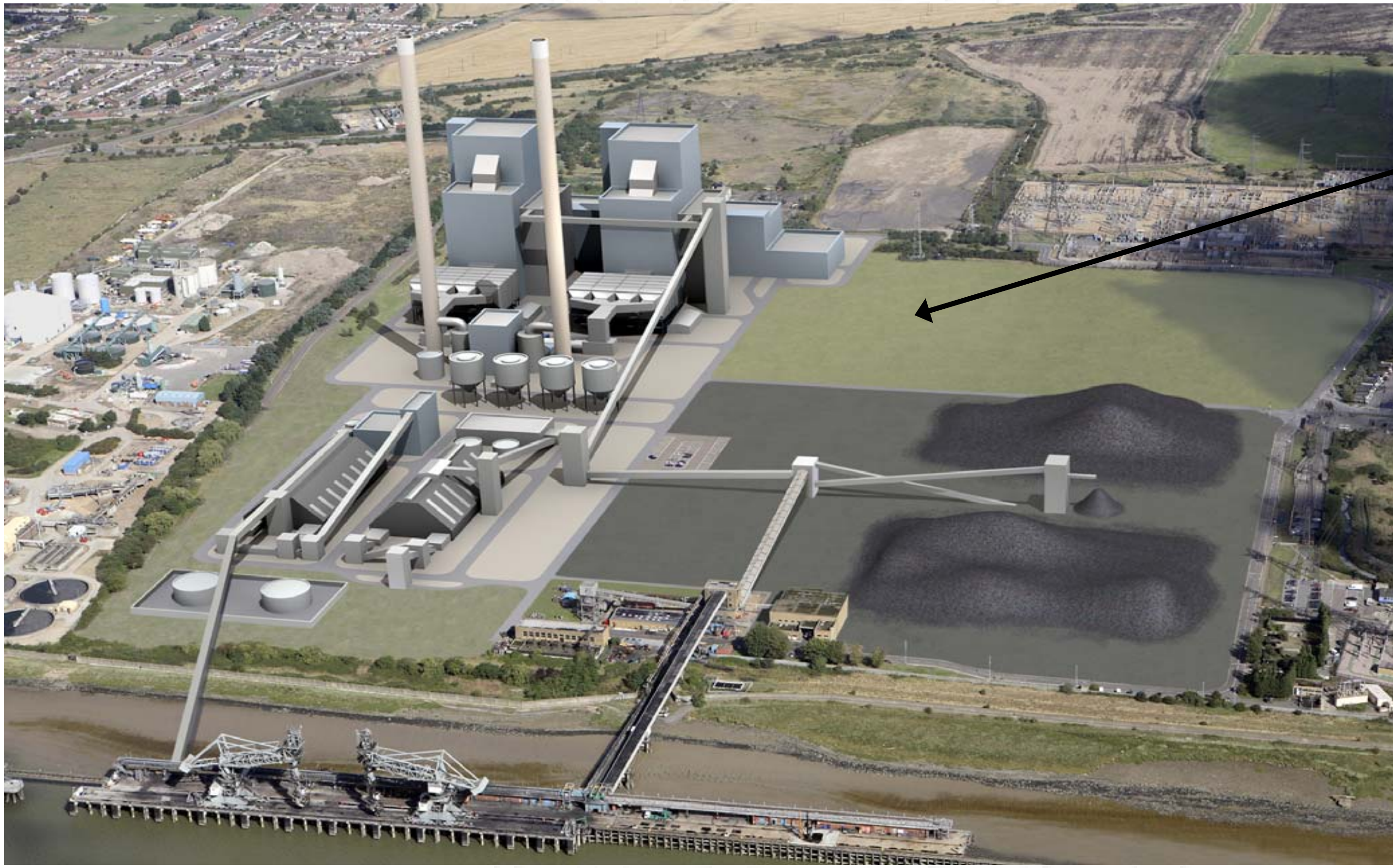
Capture Ready Requirements

- 'Essential' requirements
  - Carry out a design study on retrofit of CO_2 capture
  - Include sufficient space and access for the additional facilities that would be required
  - Identify reasonable route(s) to storage of CO_2
- Optional pre-investments
  - To reduce the downtime and cost of capture retrofit
  - To optimise the plant operation after retrofit

Essential Requirements: Space and Access

- Space for new equipment etc
  - Oxygen plant, flue gas cooler, CO_2 compressor etc
  - Electrical distribution, cooling water, waste water treating etc
  - Safety barrier zones, if required
  - Extra space needed during construction
- Space for access within the existing plant
  - Pipe work and tie-ins with existing equipment
- Additional generating capacity, if required
  - CO_2 capture usually reduces net power output
    - By about 20% for current oxy-combustion technology
  - May need to build new capacity to maintain the site power output

CO_2 Capture Ready Plant



Proposed 'capture ready' power plant at Tilbury
(One of the possible options for this site)

Courtesy of RWE Npower

Essential Requirements: Access to CO_2 Storage

- Where are potential CO_2 stores?
- What are their capacities?
- How to transport CO_2 to the stores?
  - Rights of way for pipelines
  - Safety
  - Public acceptance
  - Proximity to other potential CO_2 sources
    - Large economies of scale for pipelines
- An alternative power plant site may be preferred

How to Establish a Credible CO_2 Store?

- Identify a broad area where a large amount of storage is expected to be available, e.g. the North Sea
- Identify specific reservoir(s)
  - What needs to be done to characterise the reservoir?
    - Seismic surveys
    - Exploratory drilling
  - Costs could be significant
- Purchase a reservoir or a contractual option to use it
  - To avoid someone else using the reservoir

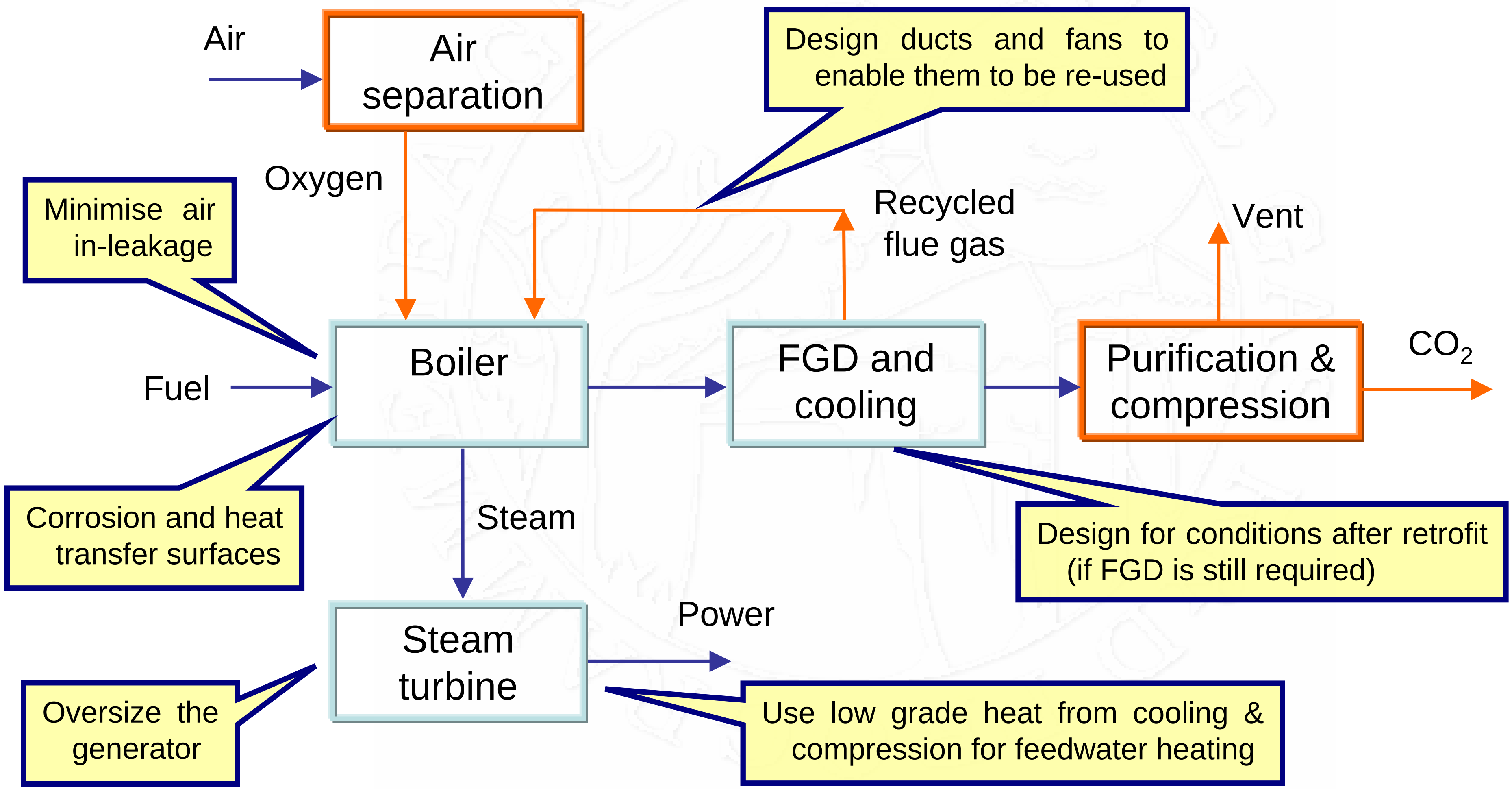
Pre-Investments – Maximising Efficiency

- The efficiency/capital cost trade-off is different for plants with CO_2 capture
  - Thermal efficiency is lower
  - Cost of generation is higher
  - The trade-off favours higher efficiency/higher capital cost designs, e.g. ultra supercritical steam cycles
- Higher efficiency designs reduce emissions even before capture retrofit
  - An important environmental benefit

Pre-Investments - General

- Oversize pipe racks etc
- Include flanges for connecting new plant
- Provision for expansion of the control system, on-site electricity distribution, cooling capacity etc
- Some of these investments are expected to have low costs and high economic returns

Pre-Investments – Oxy-Combustion



Reasons for not Making Pre-investments

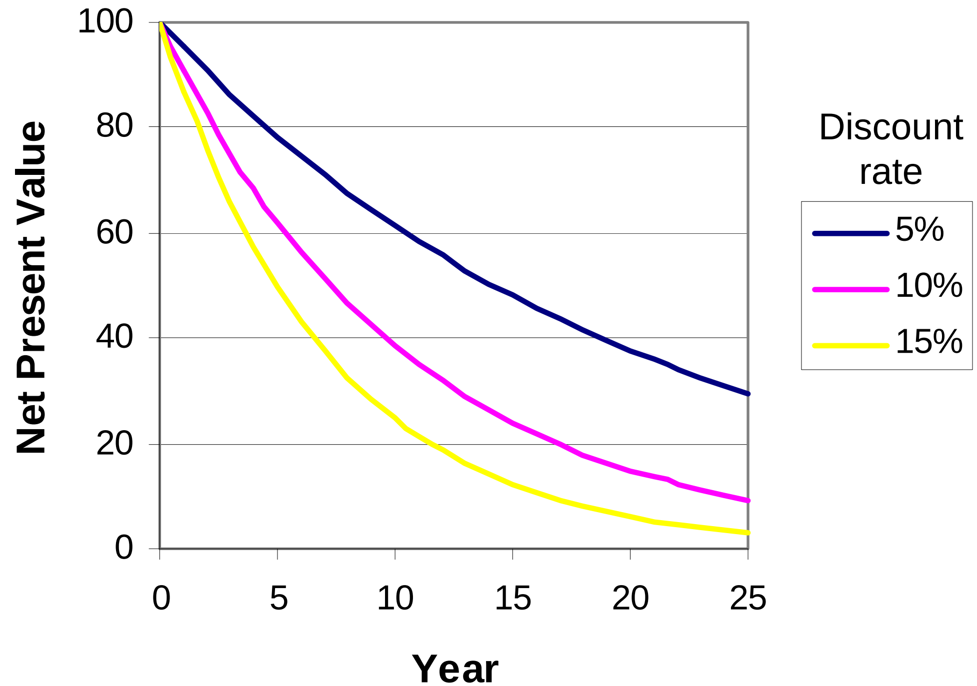
- Uncertainties
- Economic Discounting

Uncertainties

- If or when will capture retrofit be required?
  - Future values of carbon credits
  - Regulatory requirements
- Current uncertainties in large scale plant designs
- How will capture technologies develop in future?
  - Capture ready plants should be designed for current technologies
  - Incremental improvements in future
  - Possibility of substantially better technologies
  - Future technologies should be considered to reduce the risk of obsolescence

Economic Discounting

- Economic resources are worth less in the future than at present
- It may be several years before capture retrofit is required



➢ ***Major pre-investment is unlikely to be worthwhile if there is a long time before capture retrofit***

Which Process is Best for Capture Ready?

- Post-combustion capture
  - Retrofit to capture ready plants is relatively simple
  - Capture ready requirements are relatively well understood but technology developments e.g. ammonia scrubbing could change the requirements
- IGCC pre-combustion capture
  - Potentially attractive option for new-build power plants with capture
  - IGCCs without capture are expected to be more expensive than pulverised coal plants – choosing IGCC is a major pre-investment
  - Capture retrofit impacts on many aspects of the plant, unless significant pre-investment has been made
- Oxy-combustion
  - Some risks for capture ready because oxy-combustion is still at the pilot plant scale
  - Plants could also be made capture ready for post-combustion as a fall-back

A Note of Caution

- Capture Ready does not reduce emissions
  - Unless a higher efficiency plant design is selected
  - In some cases emissions may be slightly higher
- Capture Ready is not a substitute for capture
- Some people may regard Capture Ready as ‘greenwash’
- Plants with capture need to be built to demonstrate technology and increase investor confidence

Conclusions

- Capture Ready can reduce the risk of Stranded Assets and Carbon Lock-in
- Main Capture Ready considerations are:
  - Carry out a study of capture retrofit options
  - Leave space and access for capture plant
  - Identify reasonable route(s) to storage of CO_2
- Major pre-investment is unlikely to be worthwhile unless capture is going to be retrofitted soon after plant start-up
- Capture Ready is not a substitute for capture

Thank you

Any questions?

3rd Oxy-Combustion Network Meeting
5th- 6th March 2008
Yokohama Symposia, Yokohama Japan

Recent Test Results on Oxy-Fuel Combustion Using the Pilot-Scale Test Facilities

6th March, 2008

T. Uchida, T. Yamada, K. Hashimoto, S. Watanabe
IHI, Japan

Contents

1. Background

2. Flue gas analysis including Hg at Oxy-fuel combustion
   - Objectives
   - Test facilities
   - Condition
   - Analysis results
   - Further analysis items

3. Behavior of Liquefied CO2 in the various recovery condition using the simulation model
   - Outline & Objectives
   - Simple simulation model & simulation results
   - Further Studyitems

4. Conclusion

***Test was performed at 18th – 29th February.**

1. Background

Oxy-fuel system is one candidate of the CO_2 recovery from the pulverized coal power plant.

Flue gas from oxy-fuel includes many types of impurities.

In the purification system, purity of CO_2 can be increased to be more than 98%.

However, the behavior of the impurities in the recovered CO_2 is uncertain during the liquefaction process.

Therefore, flue gas analysis data for the oxy-fuel combustion and the behavior of the impurities during the liquefaction process are measured using the pilot-scale combustion test facilities.

2. Flue gas analysis including Hg at Oxy-fuel during combustion and CO2 liquefaction process

Objectives

* To obtain the analysis data of flue gas and Hg using the pilot-scale oxy-fuel combustion test facilities.

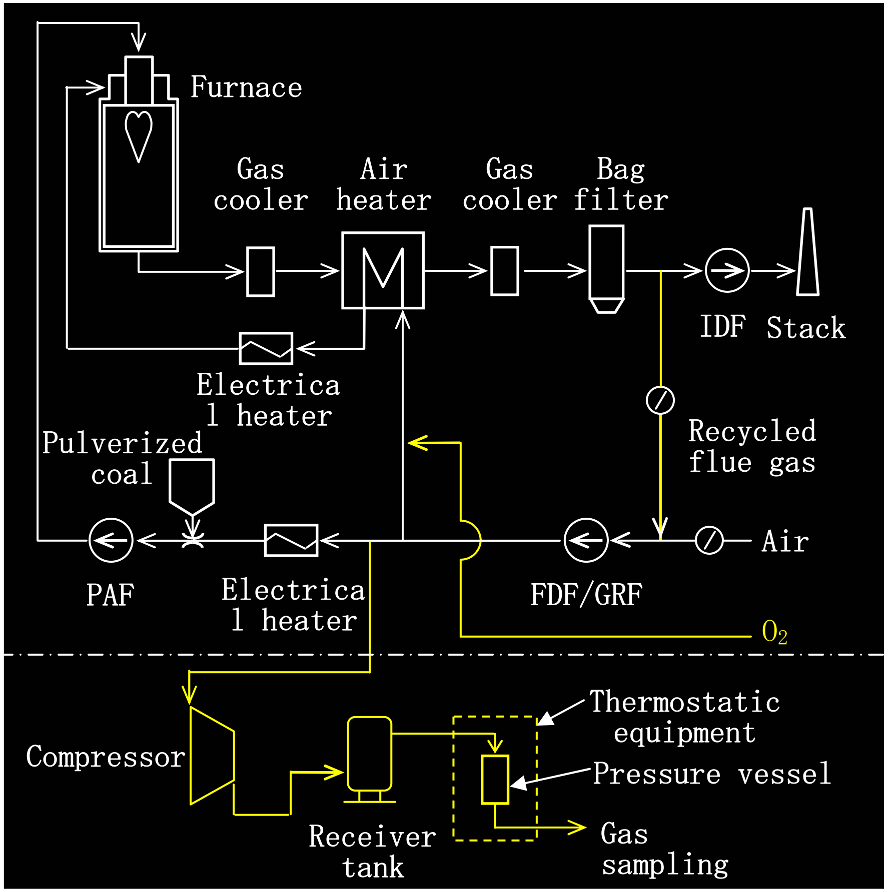
*To obtain the analysis data of liquefied CO2 from the actual flue gas of oxy-fuel combustion in order to have the basic data during the CO2 liquefied process.

Coal analysis data

Items		Coal A	Coal B
HHV	MJ/kg as fired	20.6	29.0
C	wt% dry	51.6	71.5
H	wt% dry	2.6	3.9
O	wt% dry	15.4	12.3
Total-S	wt% dry	0.1	0.6
N	wt% dry	0.3	0.4
Ash	wt% dry	24.7	8.1
Moisture	wt% dry	5.3	3.2
Hg	μg/kg dry	50	10

Test facilities

System configuration



Combustion test facilities

Furnace	Vertical furnace (Top burner)
Size	I.D. 1.3m × L 7.5m
Burner	Swirl & stabilized type
Capacity	1.2MWth

CO2 liquefaction test facilities

Maximum pressure	4.5MPa
Temperature	N.T. to −70℃

Combustion test facilities

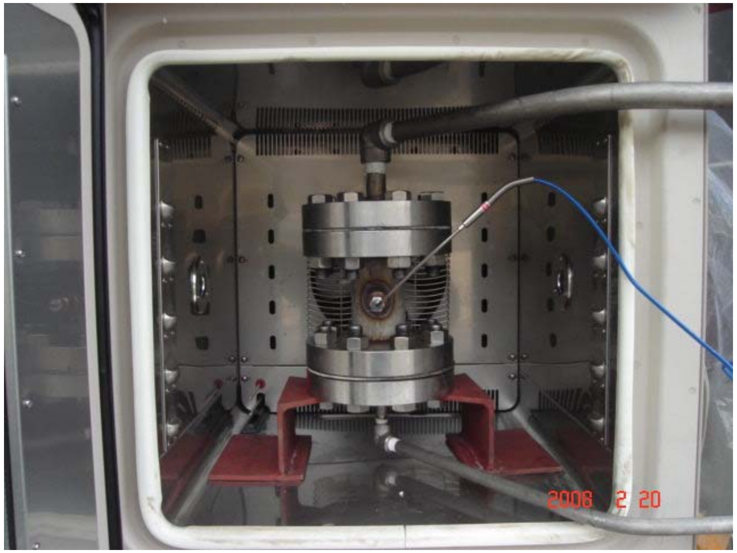
Overview

Gas flow

Furnace with inspection hole

CO2 liquefaction test facilities

Compressor
(Recipro & Oil free type)



Pressure vessel in the thermostatic equipment

Combustion condition

Coal	-	Coal A	Coal B
Combustion mode	-	Oxy-fuel	Oxy-fuel
PC feed rate (Heat input)	kg/h (MW)	120 (0.7)	90 (0.7)
Fineness (under 74μm)	%	75～80	75～80
Flue gas O2 conc.	vol%dry	3.3	3.3
O_2 conc. in Wind-box	vol%wet	33	33
Total O2 conc. to the furnace	vol%wet	27	27

Test results of CO2 conc. at the several point

Sampling point	-	Coal A	Coal B
CO2 conc. at AH inlet	vol%dry	63.2	72.0
CO2 conc. at BF inlet	vol%dry	60.5	70.6
CO2 conc. at recirculation point	vol%dry	53.1	64.0
CO2 conc. at the branch point to liquefaction test facilities	vol%dry	50.7	56.4
CO2 conc. at the compressor outlet	vol%dry	49.0	53.5

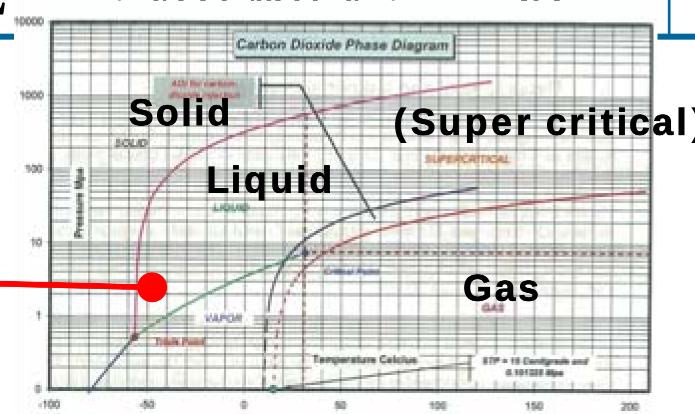
*Furnace is the negative pressure, approx. -0.1kPa.

*Total volume of air ingress is 8 - 10 % for the volume of flue gas in our calculation.

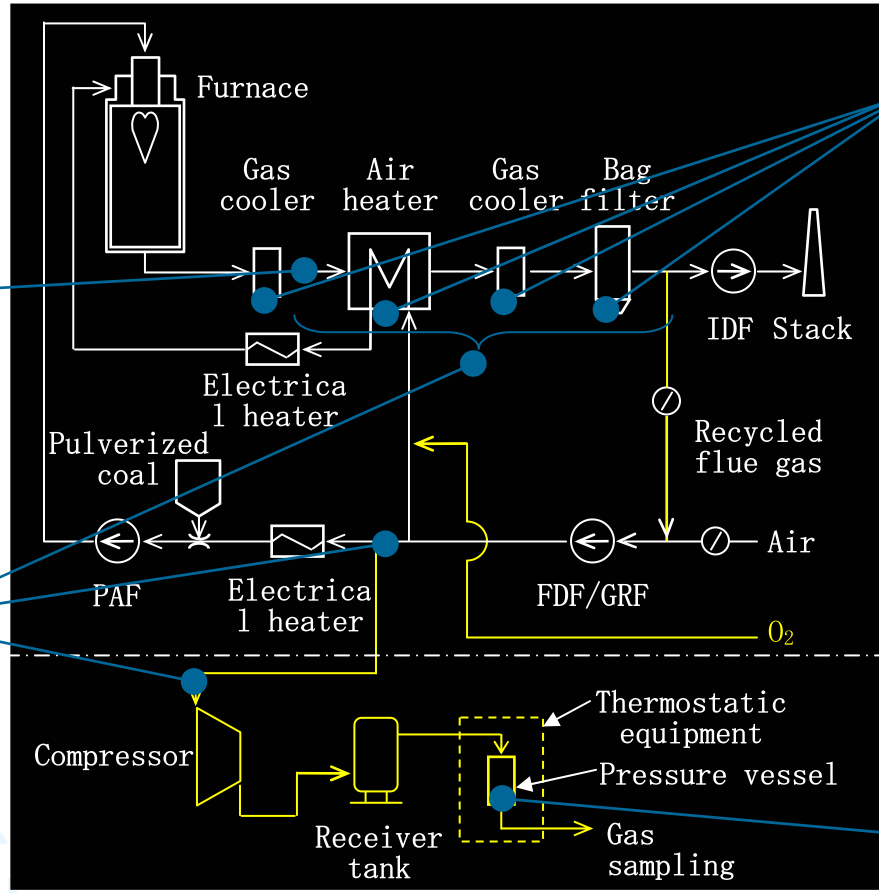
Test results of CO_2 liquefaction test

Items		Coal A	Coal B
CO_2 conc. at compressor outlet	vol%dry	49.0	53.5
Pressure in the vessel	MPa	4.5	4.5
Partial CO_2 pressure in the vessel	MPa	2.2	2.4
Temperature	℃	−50	−50
CO_2 conc. of liquefied CO_2	vol%dry	98	97

〈Ref.〉 CO_2 liquefied condition



Further analysis items



Carbon-in-ash & Hg in collected Ash

HCl & HF at AH inlet

Hg^{0} & Hg^{2+} in flue gas

Hg in liquefied CO2

<Sampling has done conducted and now on analysis>

3. Behavior of Liquefied CO_2 in the various recovery condition using the simulation model

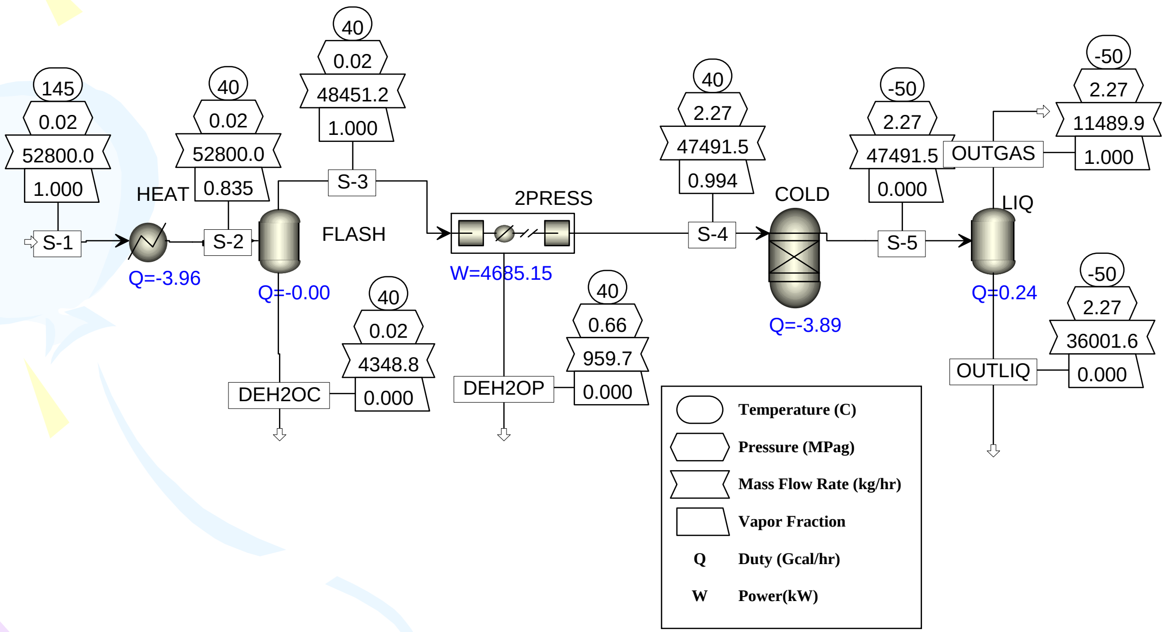
Objectives

*To obtain the knowledge of recovered CO_2 during the liquefaction process
- Modeling the simple liquefaction process
- Reflection of the analysis data at CO_2 liquefaction test

*To evaluate the behavior of the impurities in the recovered CO_2 at the next step

Simulation model

Simple process of the liquefaction test is simulated by Aspen as below.



Inlet flue gas (base)

CO_2: 62Vol%

H_2O: 20Vol%

O_2: 3.7Vol%

N_2: 12Vol%

Ar: 1.3Vol%

Hg : 1.03 μ g/Nm^3

Temp. 145℃

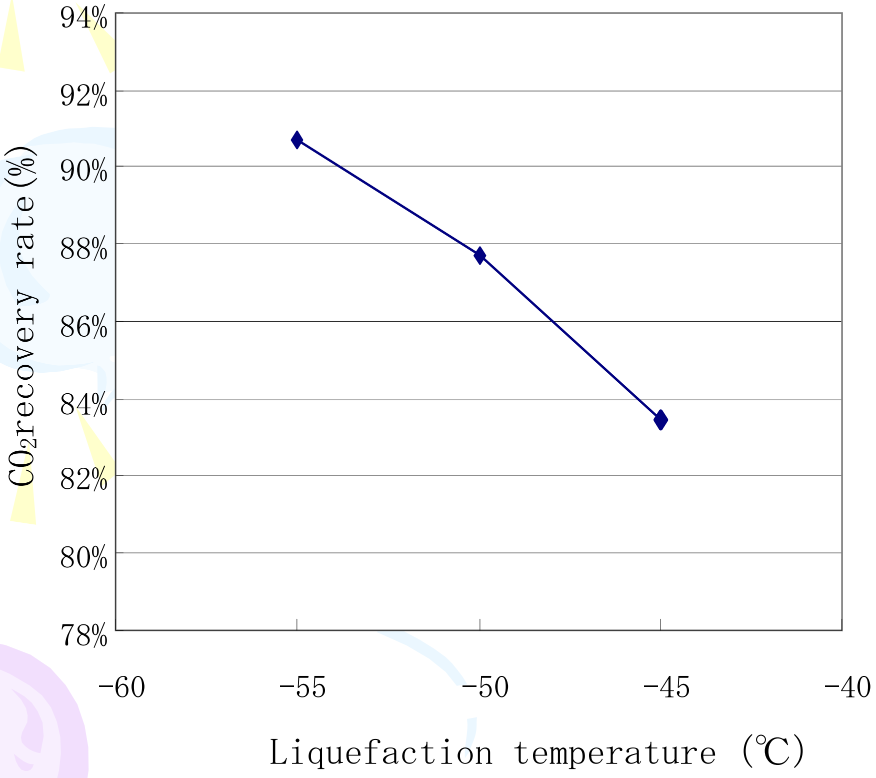
Draft 0.02kPa(g)

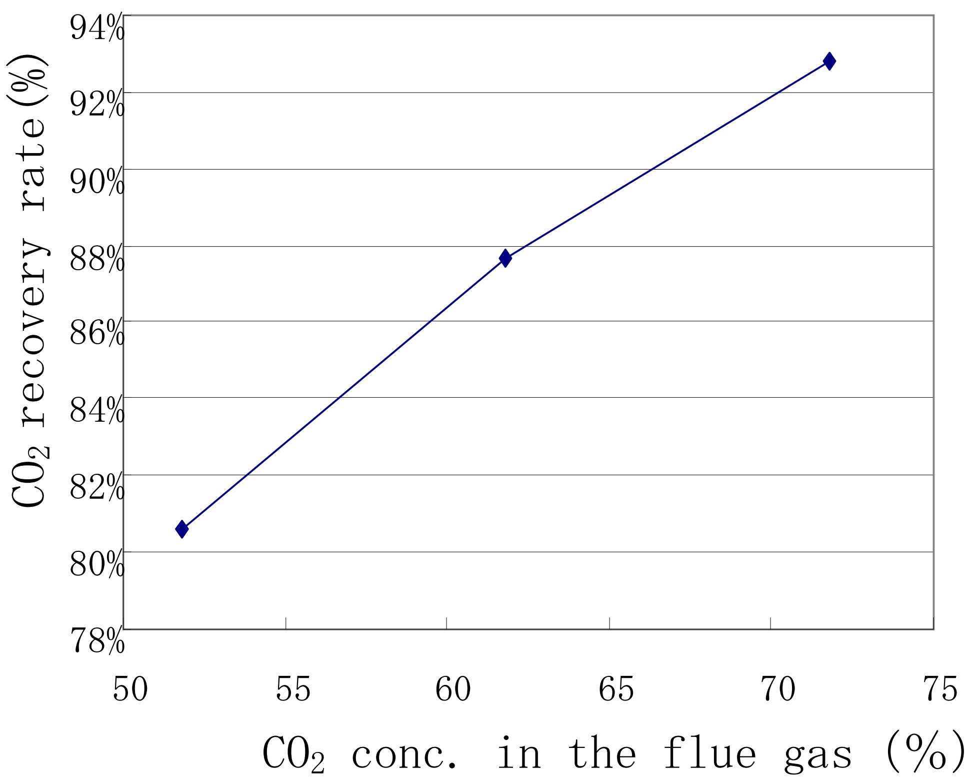
〈Liquefaction condition〉

−50 ℃/2.4MPa

Simulation results

Behavior of CO2 recovery rate was confirmed at the various condition.





Further study using the simulation model

*To confirm the behavior of Hg at the various CO2 liquefaction condition

*To compare the results of CO2 and Hg analysis data of CO2 liquefaction test and to reflect to the simulation model

Conclusions

We will be able to obtain much information from the results of combustion test and liquefaction test and reflect such data to simulation model.

Our target is to evaluate the behavior of CO_2, Hg etc. through the oxy-fuel combustion and the purification system using the upgraded simulation model in the near future.

Acknowledgement

"Thank you for your attention!"

power generation group

AIR LIQUIDE

Oxy-Coal Combustion Pilot

IEAGHG International Oxy-Combustion Network;
Yokohama, Japan; Mar. 5-6, 2008

H Farzan, DK McDonald, KJ McCauley; Babcock & Wilcox
R Varagani, R Prabhakar, C Periasamy, N Perrin; AirLiquide

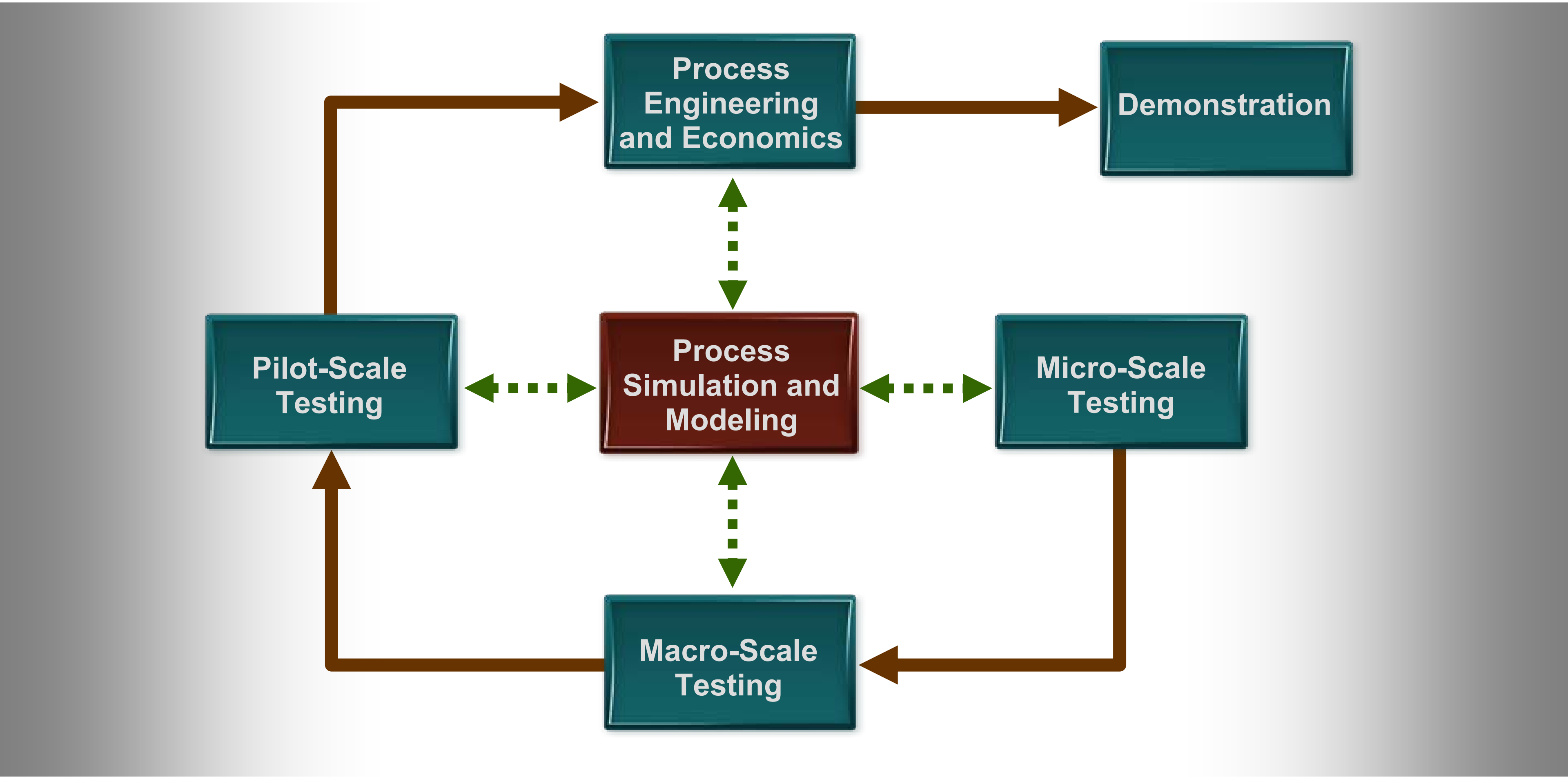
Kevin J. McCauley
Manager, Strategic Planning

Why Oxy-Coal Combustion?

Oxy-coal combustion has reasonable potential to be the lowest cost, highest efficiency, most reliable and easiest to deploy large scale carbon capture technology.

- **Next generation improvements in progress**
  - USC technology development
  - Reduction of recycle
  - Simplified moisture removal
  - Elimination of gas reheating
  - Total plant integration

New Product Commercialization – R&D Process

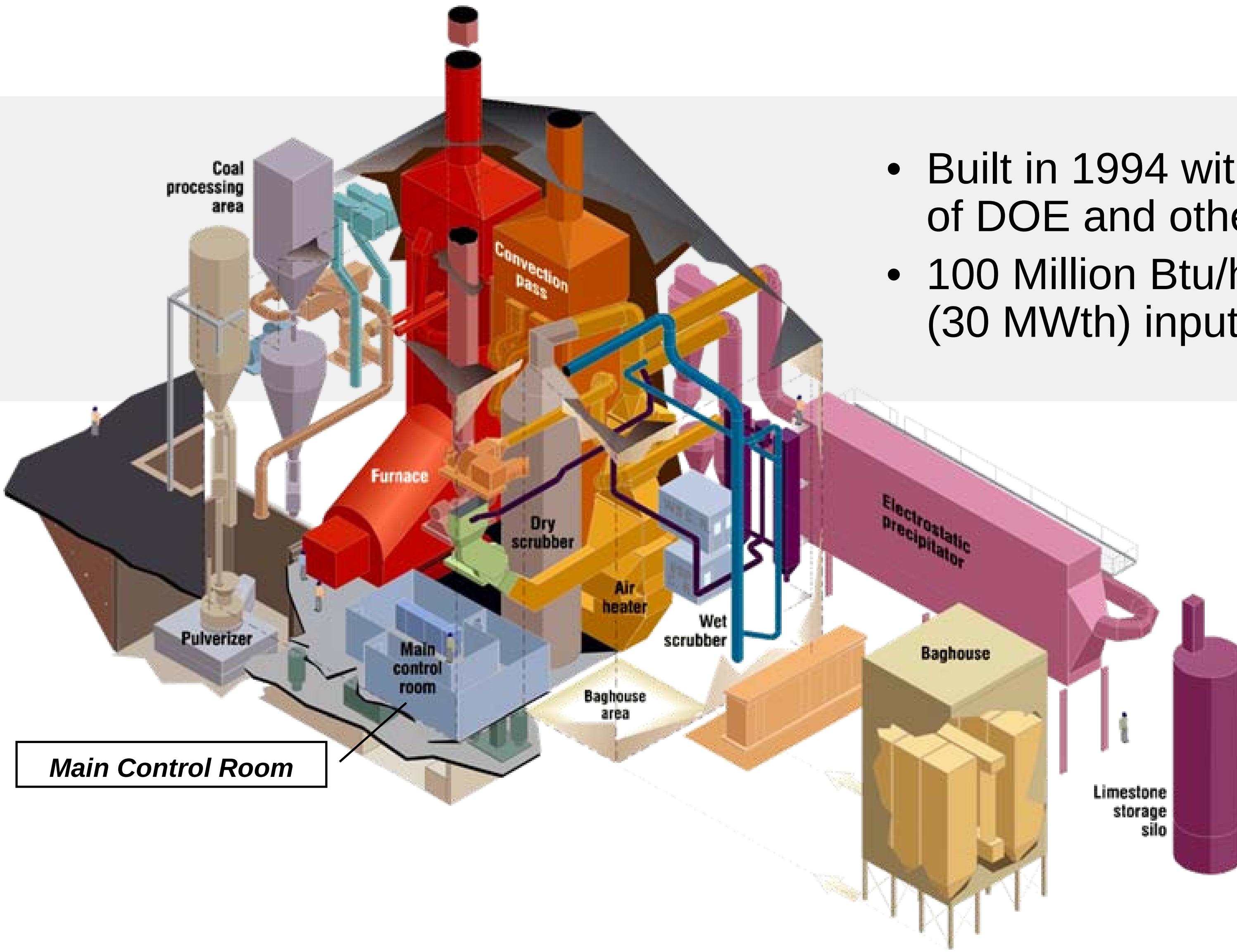


30 MW_{th} Oxy-Coal Tests at B&W Clean Environment Development Facility (CEDF) for CO_2 Capture

- Managed and funded by B&W, American Air Liquide, Inc. and Utility Advisory Group
- CEDF modified to use and mix oxygen, added WFGD, other auxiliary equipment for oxycoal
- Utility Advisory Group providing end user design feedback for commercial applications
- Test campaigns underway include Saskatchewan lignite, sub-bituminous (PRB) coal and eastern bituminous coal

AEP
AES
BASIN ELECTRIC POWER COOPERATIVE
EPRI
FirstEnergy
minnesota power
MidAmerican ENERGY
MONTANA-DAKOTA UTILITIES CO.
SaskPower
PACIFICORP ENERGY
SOUTHERN COMPANY
AIR LIQUIDE

30 MW_{th} Test Facility located in Alliance, Ohio



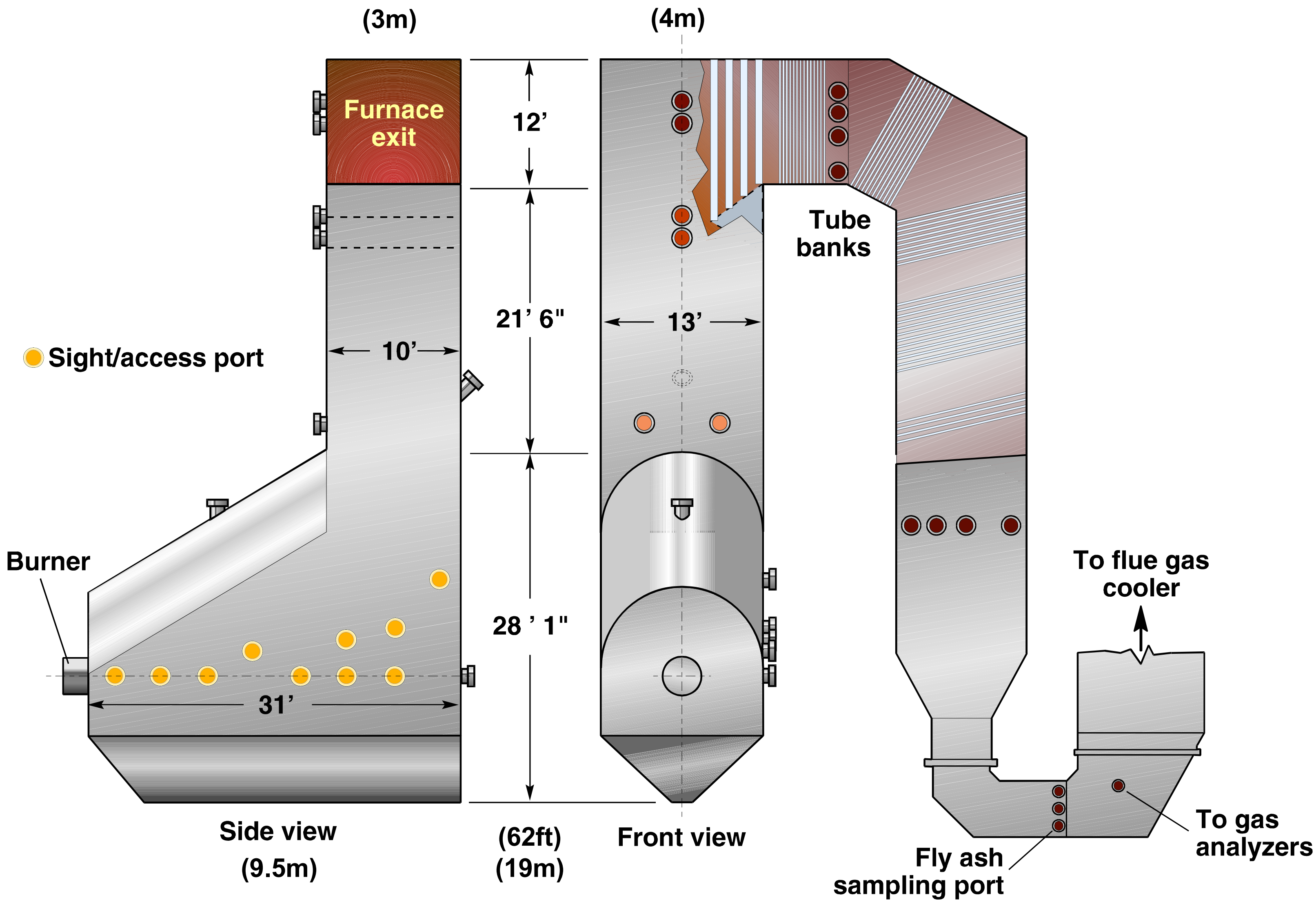
- Built in 1994 with support of DOE and others
- 100 Million Btu/hr (30 MWth) input with coal

CEDF Oxy-coal Campaign

Expected Major Goals

- Optimum burner design for each coal
- NO_x emissions
- Floxynator performance
- Pulverizer performance
- Furnace exit gas temperature
- Boiler/convection pass heat transfer
- Scrubber performance
  - SO_2 Control
  - SO_3
- Potential enhancement of mercury speciation with oxy-combustion
- ESP performance
- Insights for materials development
- Air infiltration evaluations (future CPU design)

CEDF Furnace Views



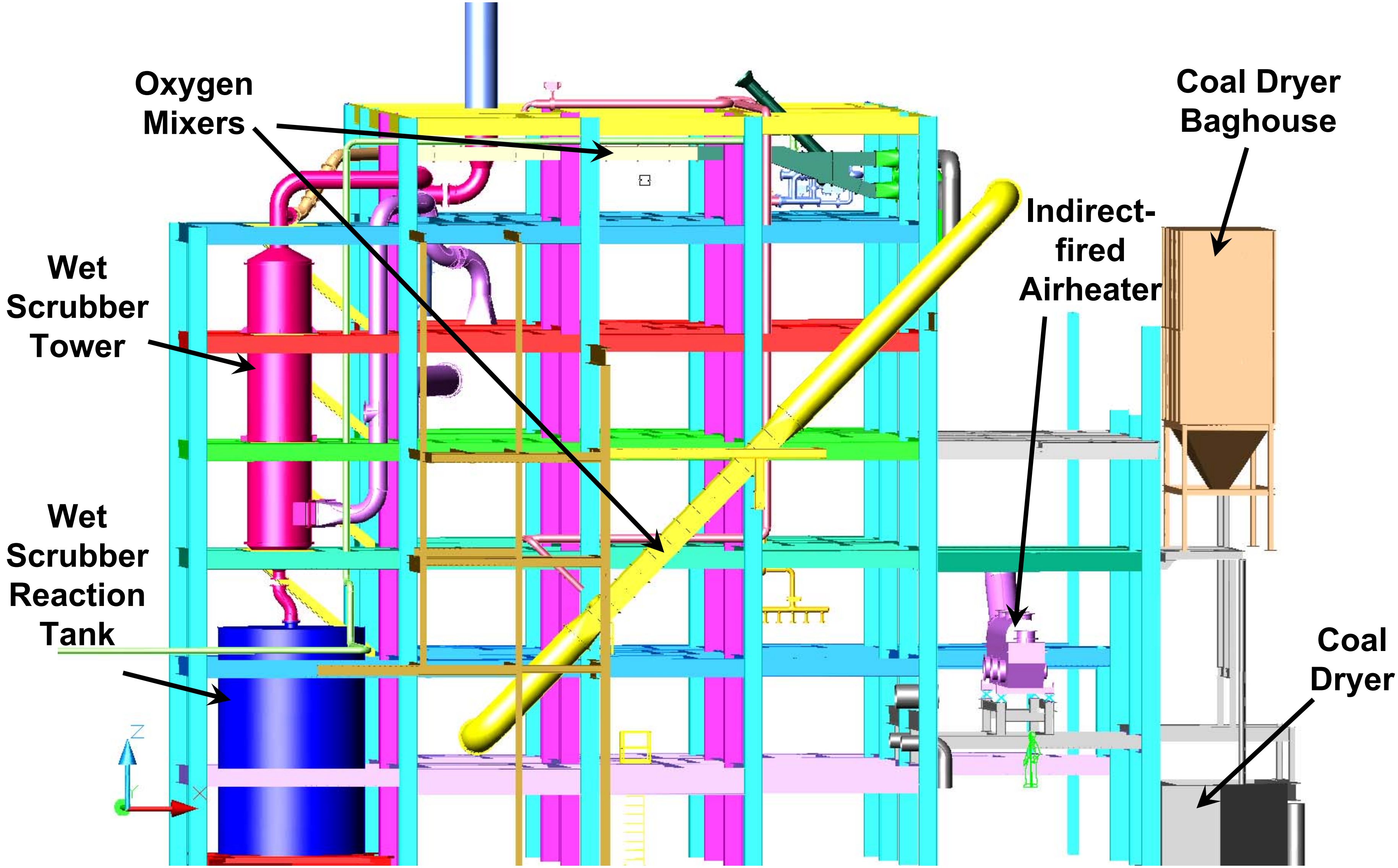
CEDF Oxy-Coal Campaign - Coals

	Mahoning 7 Eastern Bituminous	Black Thunder Western Sub-Bituminous	Shand Lignite
C	73.30	50.66	39.62
S	1.37	0.33	0.51
H	4.97	3.58	2.54
H_2O	4.73	27.43	34.19
N	1.52	0.65	0.54
O	6.62	12.13	10.18
Ash	7.49	5.22	12.42
HHV, Btu/lb	13,124	8,758	6,495
HHV, kJ/kg	30,251	20,367	15,104

CEDF Modifications for Oxy-coal Testing

- Recycle flue gas system and air intakes
- Oxygen supply and mixing system
- Moisture removal system
- Full flow wet flue gas desulphurization (WFGD) system
- Capability to direct fire (indirect-fired heater)
- Coal dryer for flexibility in testing
- Furnace panel for assessing heat flux and emissivity
- Instrumentation for data acquisition and control
  - Desired process parameters
  - Gas compositions at key locations
  - Mercury at selected locations
- Controls upgrade for new equipment
- Maintenance and preparation of existing equipment
  - Replace furnace refractory
  - Upgrade fan shaft seals
  - Service and refurbish all existing equipment

CEDF Modifications for Oxy-coal Testing



Oxy-coal CEDF - SO_2 Scrubber system installation

Recirc & Bleed Pumps

Tower Inlet Flue

WFGD Tower

240 tons/day Oxygen supply and distribution system

11,000 gal and 52,000 gal LOX tanks installation

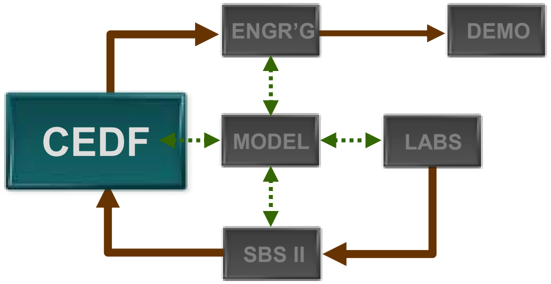
Sec. Floxynator^{TM} installation

LOX tanks & Ambient vaporizers

AIR LIQUIDE

Oxygen distribution system

CEDF Oxy-coal Program

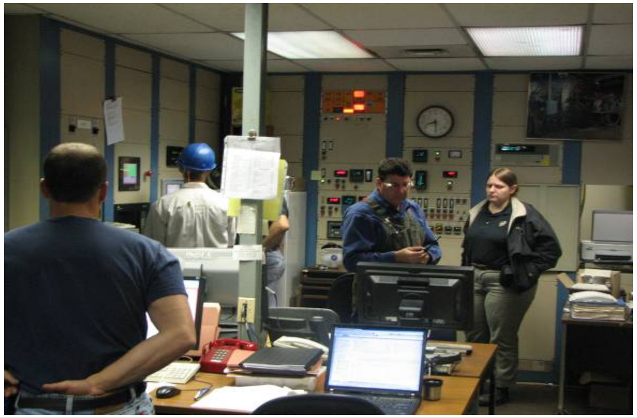


- **Project Timeline**
  - Jan 2007: Start site demolition/construction
  - Jun 2007: Most major construction complete
  - Aug 2007: Component shakedown completed
  - Sep 2007: First fire on coal with oxygen
  - Oct 8 2007: First full oxy-transition at 80 MBtu/hr
  - Oct 2007: Begin baseline tests
  - Nov 2007: Three days continuous operation on oxygen, with bituminous coal
  - Dec 2007: First test campaign complete, 100+ hours
  - Early 2008: Lignite and sub-bituminous testing

Oxy-combustion CO_2 Control – 2007 Highlights

100+ hours in oxy mode (bituminous coal)

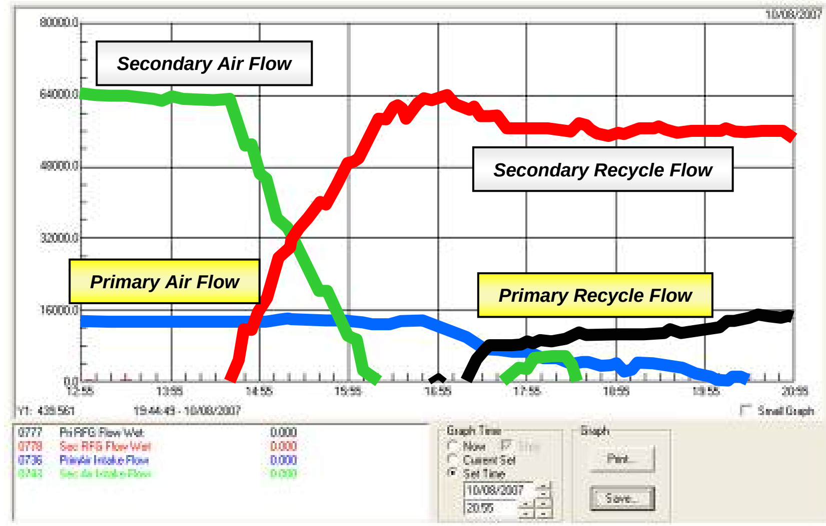
Oxy-coal Flame

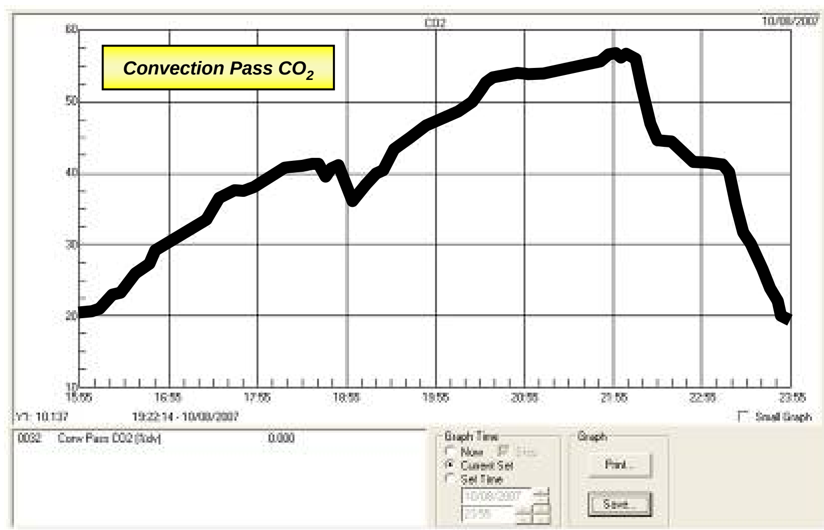


AIR LIQUIDE

CEDF Baseline Test Campaign #1

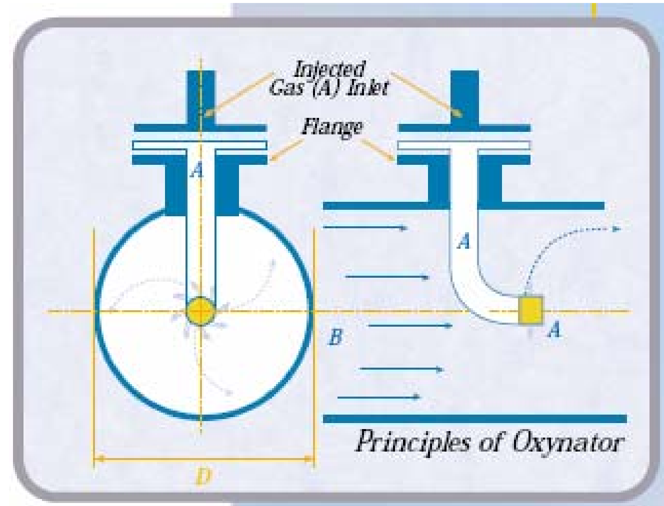
- **Test Plan Objectives**
  - Establish baseline for three major fuel types
  - Verify process parameters for full scale design
    - Multiple burner configurations, with pulverizer
    - Flue gas recycle with commercial O_2 mixing system
    - Wet scrubber
    - Flue gas moisture control
- **Results to Date**
  - CO_2: 70% (dry volume), air infiltration high
  - NO_x: Similar to SBS tests, SBS achieved 60% reduction
  - CO: Low
  - SO_2: No noticeable change in wet scrubber removal
  - Transition: First two very smooth over several hours in manual
  - Stability: Burner very stable, brighter flame vs. air

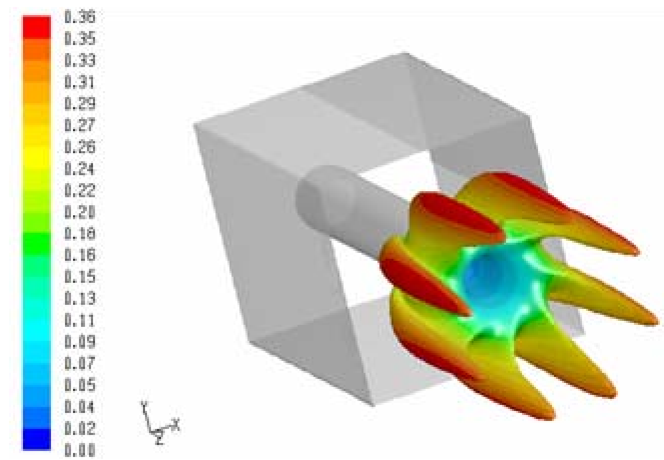




Floxynator™* for O_2/FG Mixing

- Based on AL's patented Oxynator™
  - Air/O_2 mixing
  - Radial injection with swirl
  - Low pressure drop
  - Commercial installations at 800 tons/day
- Challenges
  - Up to 10,000 tons/day O_2 mixing
  - Large turndown
  - Additional safety constraints
    - Flue gas impurities
    - Coal handling
- Floxynator™
  - Mixing in the center, safe-guarding the duct walls
  - Extensive numerical and bench scale tests
- Floxynator™ concept successfully validated at CEDF





* TM, Patent pending

Oxy-combustion CO_2 Control – 2007 Highlights

LESSONS LEARNED SO FAR:

1. The process works.
2. Oxy flame is bright and stable
3. NOx is significantly reduced (>50%)
4. SO_2 removal not significantly different than with air
5. Safe and efficient mixing of O_2/flue gas with Floxynator
6. There's more air infiltration at CEDF than expected
7. Transition is very controllable in both directions
8. Unit tripping at high load on oxygen is safely manageable and anticipated control scheme works


Temperature: 053 F
Camera ID

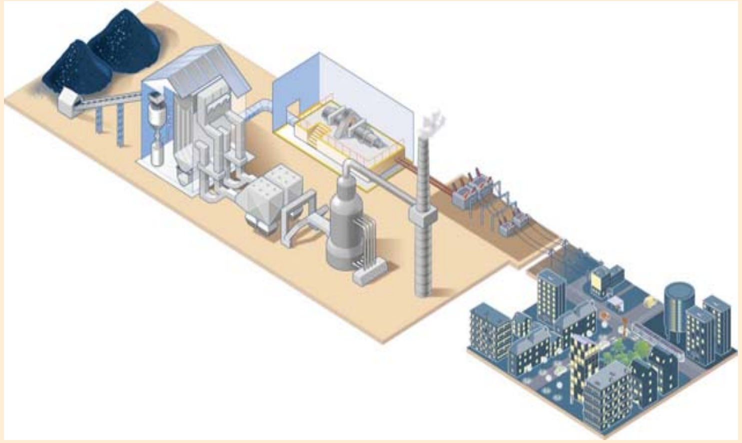
Dōmo Arigatō Gozaimasu

Alstom Development of Oxyfuel PC and CFB Power Plants

Frank Kluger & John Marion

3rd Oxy-Combustion Workshop
Yokohama, Japan
March 06, 2008

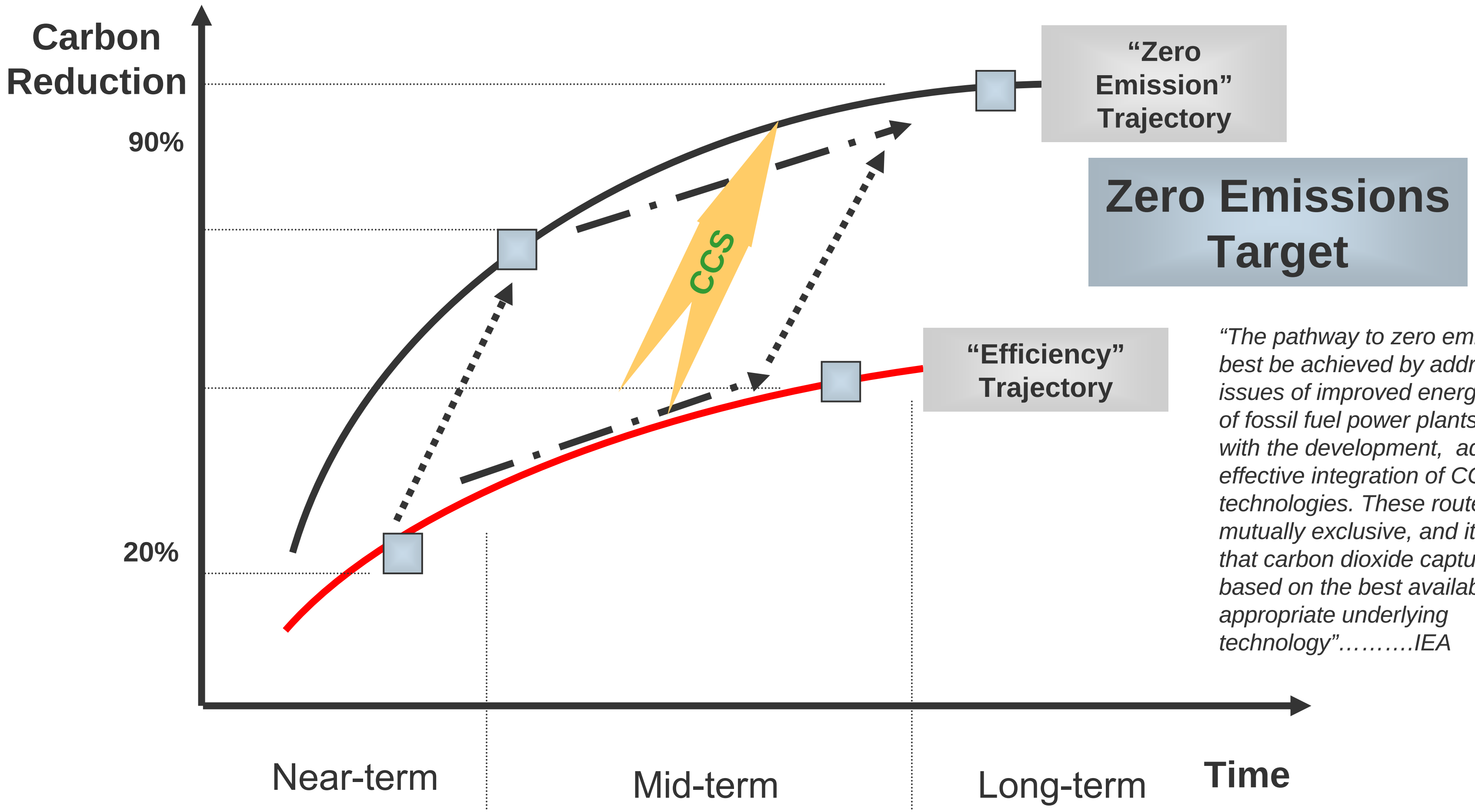
Improvement Measures for Fossil Power Plants Regarding CO2 Mitigation



1 Efficiency Increase

2 CO_2 Capture & Storage

Pathway to “Zero Emission Power” for Fossil Fuels



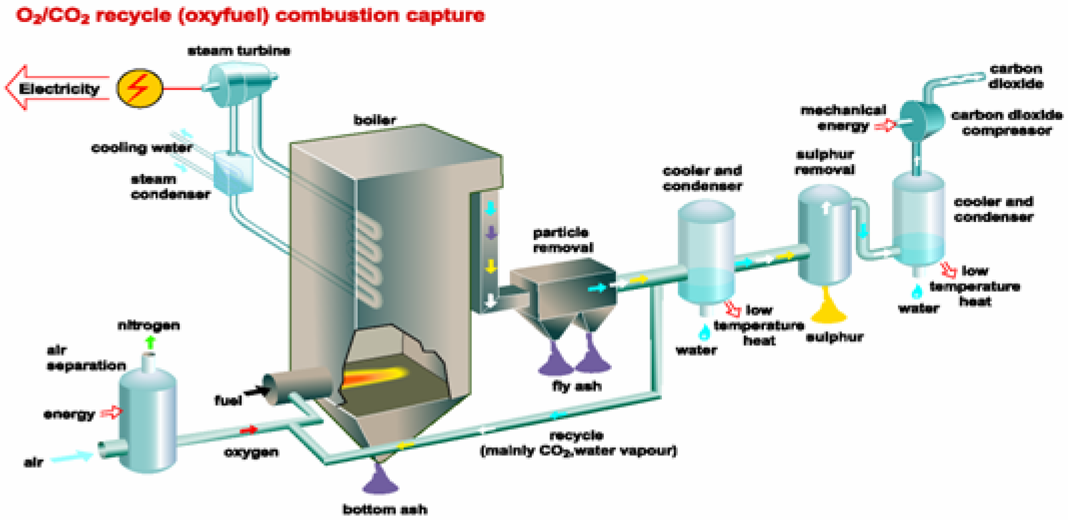
“The pathway to zero emissions can best be achieved by addressing the issues of improved energy efficiency of fossil fuel power plants together with the development, adoption and effective integration of CO2 capture technologies. These routes are not mutually exclusive, and it is essential that carbon dioxide capture plant is based on the best available and appropriate underlying technology”……….IEA

Integrated strategy for `zero emission`

Oxy-fuel Firing

- Complementary with conventional boiler and steam power plant technology, including efforts towards ultra-supercritical conditions (for efficiency improvement), as well as environmental control developments

- Applicable for new and retrofit plants



Oxy-combustion opportunities and challenges

Opportunities

- Low technological risk option
- Large power plant size possible
- Repowering and Retrofit possible

- All boiler technologies adaptable
- Fuel flexibile
- Steam Cycle increases possible

- Potential boiler size reduction
- Advanced O2 supply

Innovation

Challenges

Cost

- Cryogenic oxygen
- CO2 Quality
- CO2 compression
- Heat flow optimisation
- Integration

Time

- On time Development

Technology

- Scale-up validation
- Adaptation to installed base
- Innovation

CO2 Product Quality Discrepancies

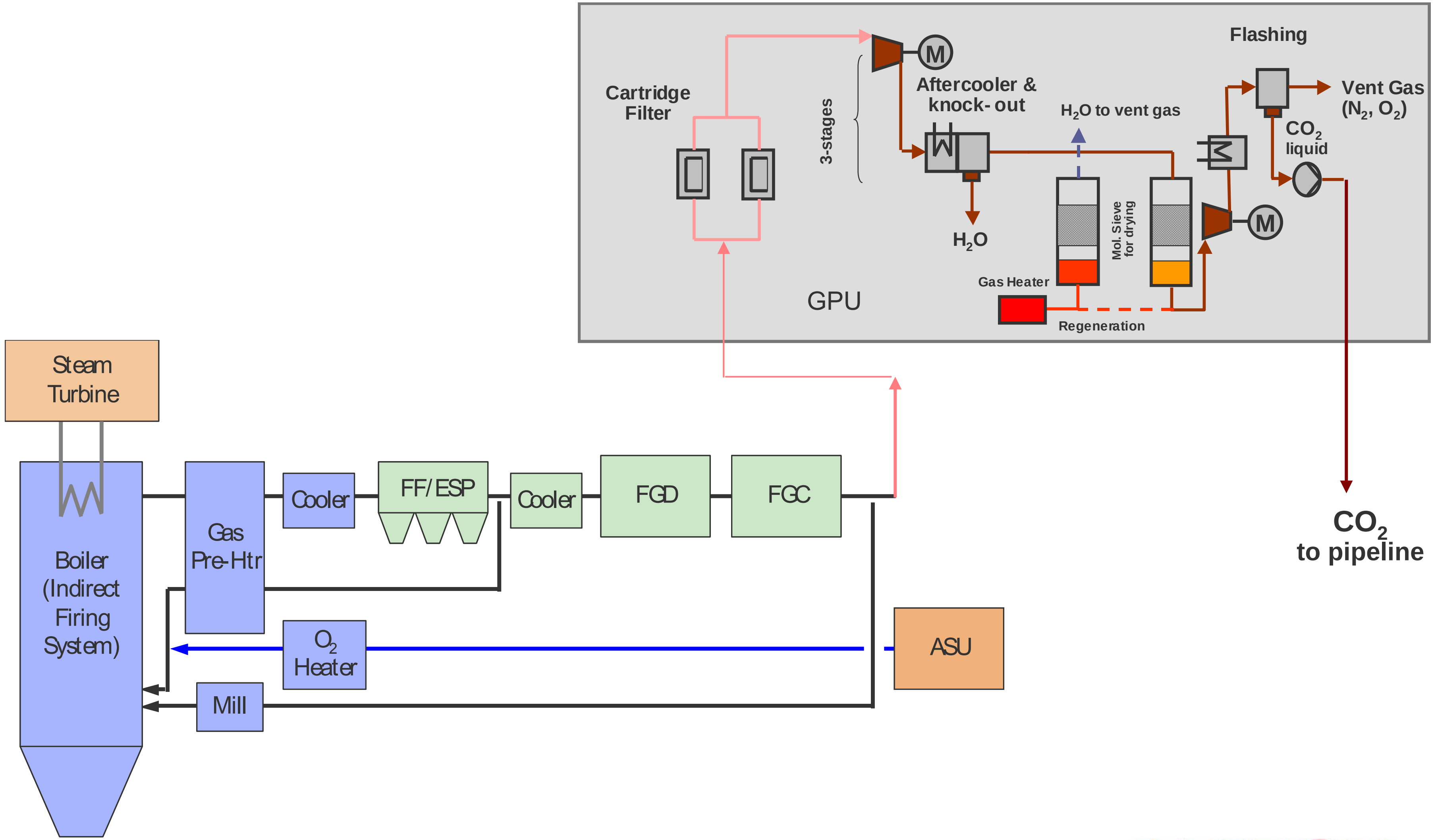
Table: Tolerances for the various contaminants of CO_2

	Tolerance	
Component	low	high
CO_2 [%]	> 90	> 95
H_2 [%]	< 4	< 4
N_2 [%]	< 4	< 4
Ar [%]	< 4	< 4
CH_y [%]	< 4	< 5
O_2 [ppm]	< 10	< 1000
H_2O [ppm]	< 10	< 600
CO [ppm]	< 100	< 40000
NO_x [ppm]	< 100	< 1500
SO_x [ppm]	< 100	< 1500
H_2S [ppm]	< 100	< 15000
Particulates [mg/Nm³]	< 0.1	< 10

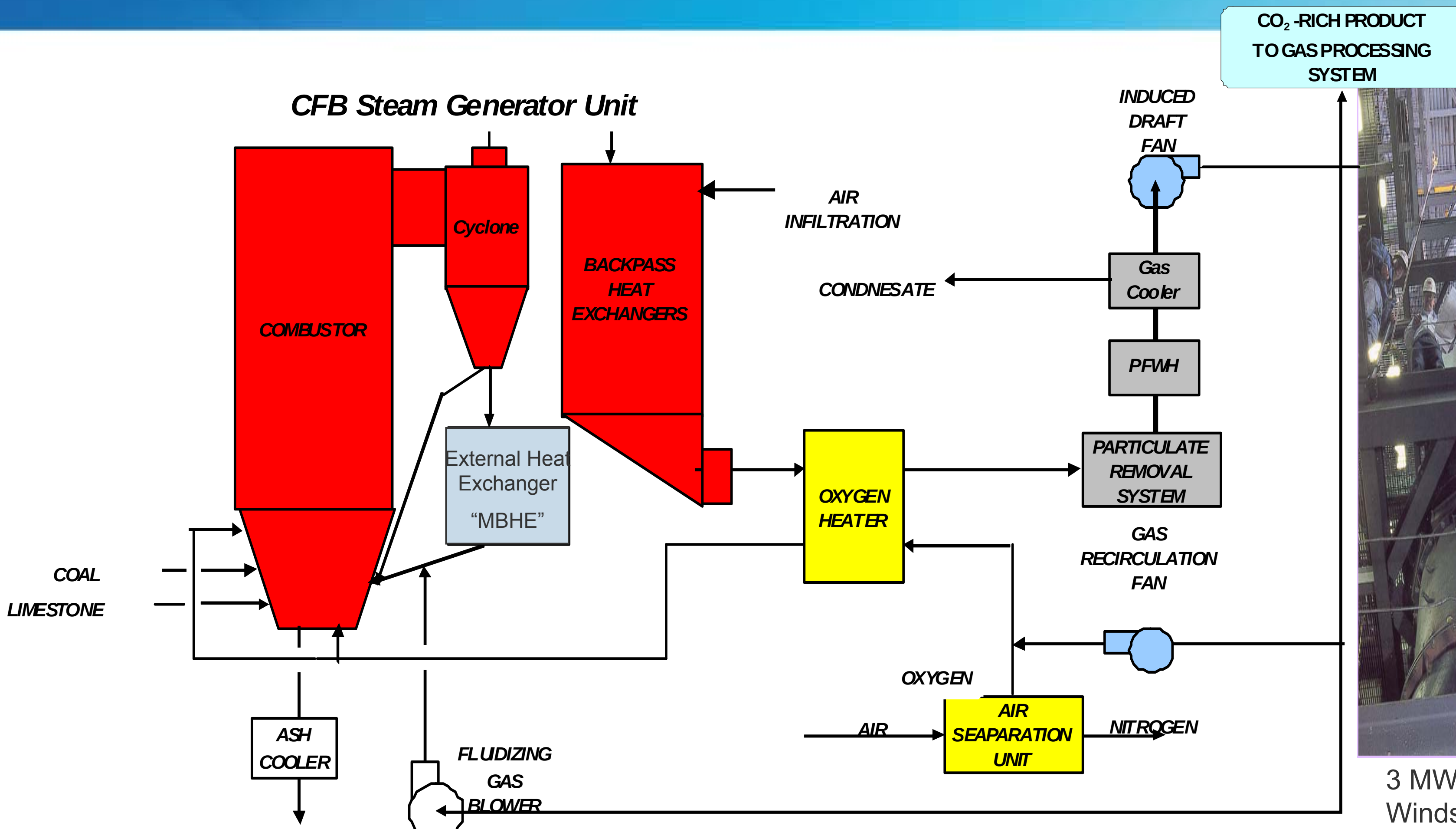
Limiting factor: EOR, H&S, Corrosion, unclear, Storage

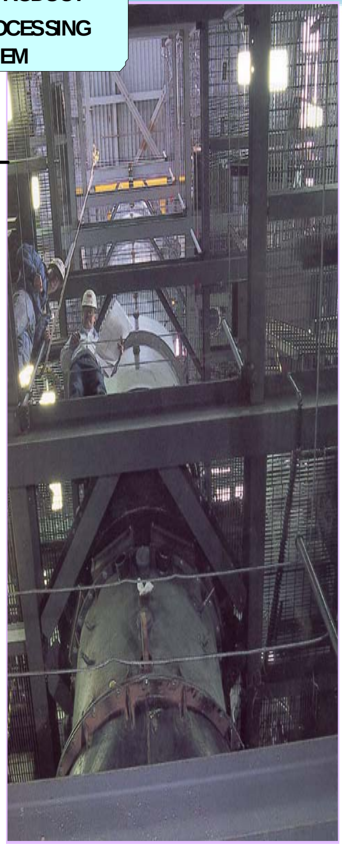
Alstom compilation from published reference data

Oxy-PC Power Plant - CO2 product quality impact on ASU, APC, and GPU equipment



Oxy-CFB Concept

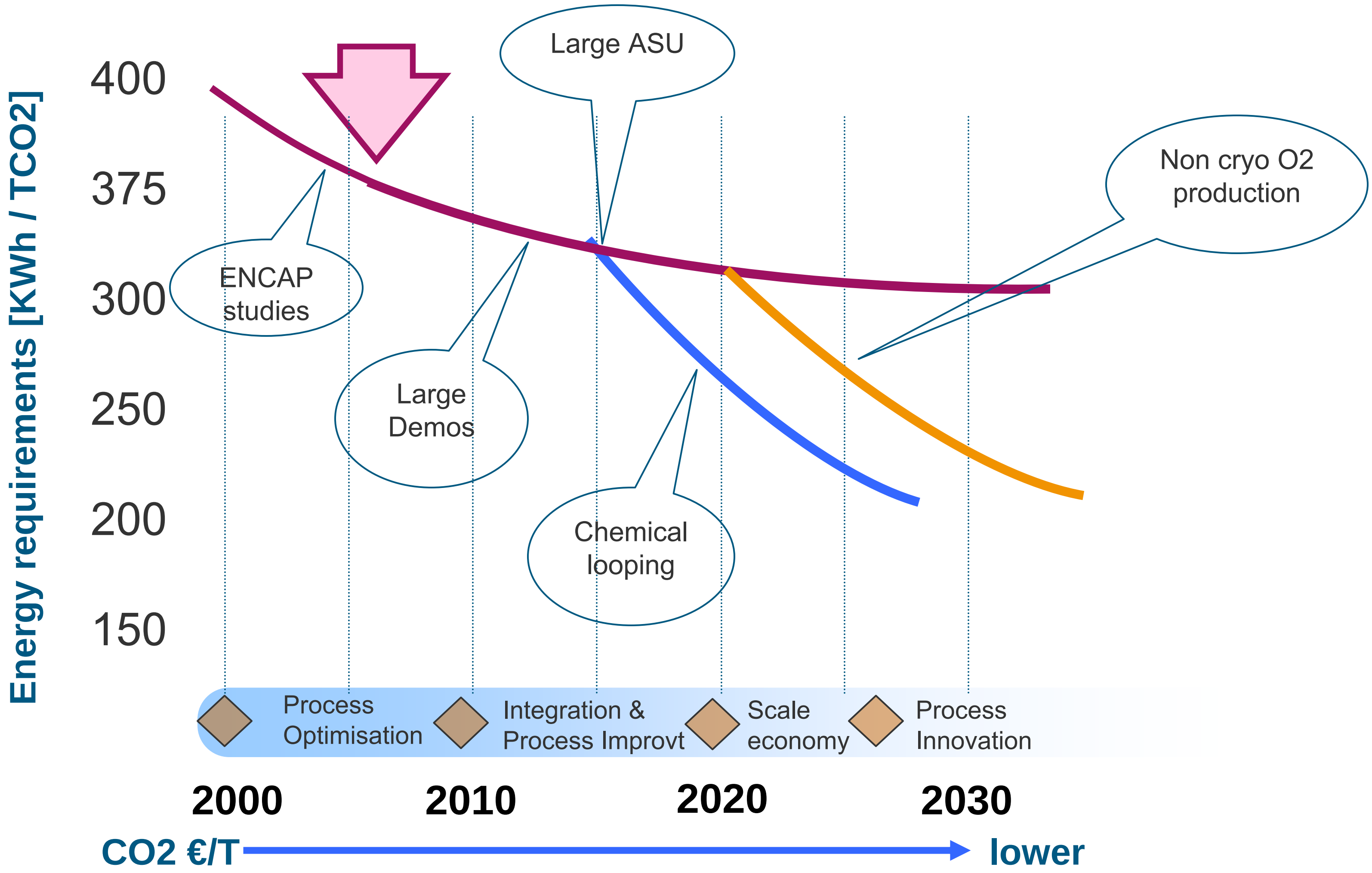




3 MWt pilot CFB Windsor, CT, USA

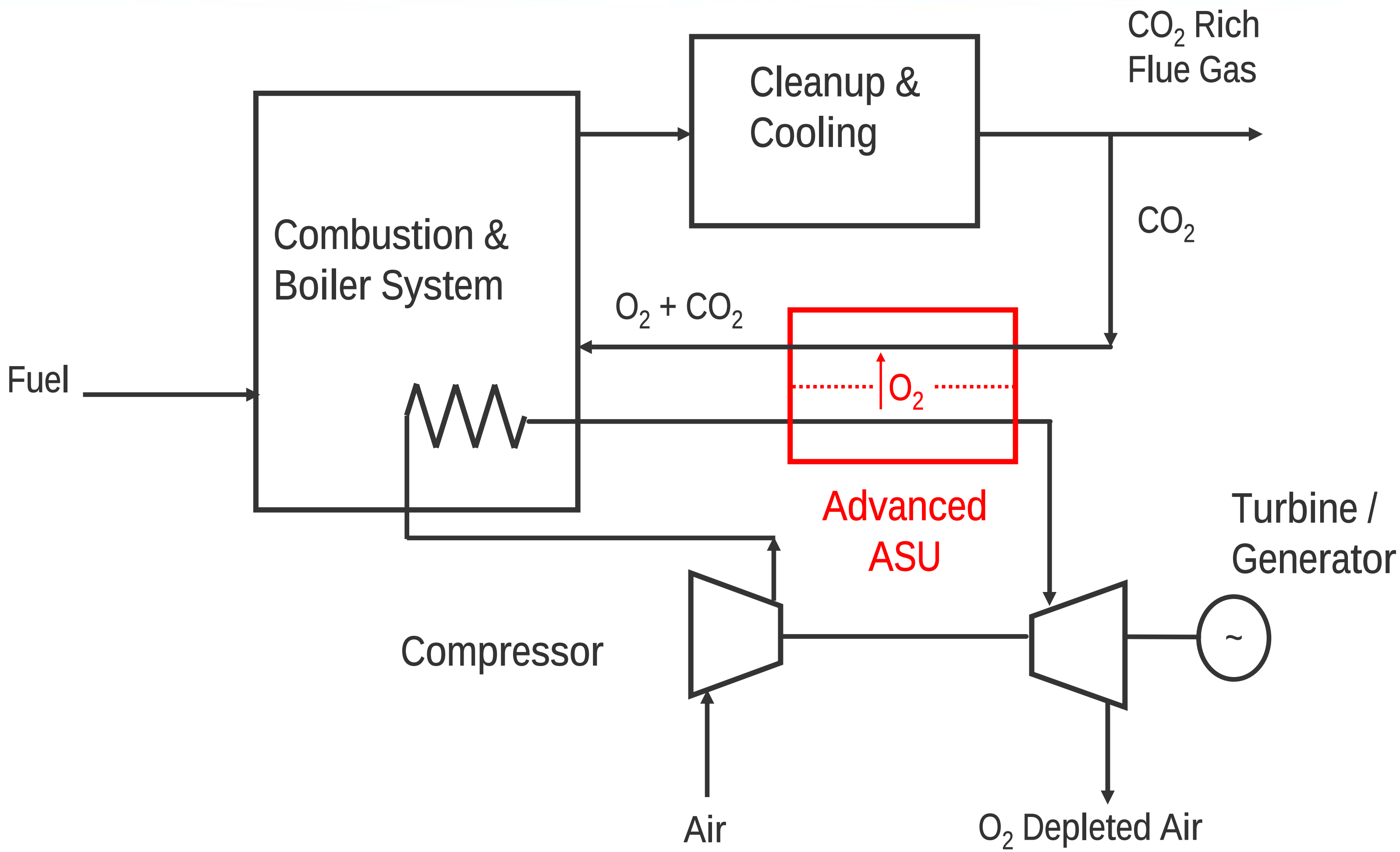
- Potential for Reduced recycle FGR and resultant smaller boiler & APC
- Market segmentation as with air-fired CFB's (low quality fuels)

Going Down The Experience Curve for Oxy Combustion CO2 Capture



ALSTOM

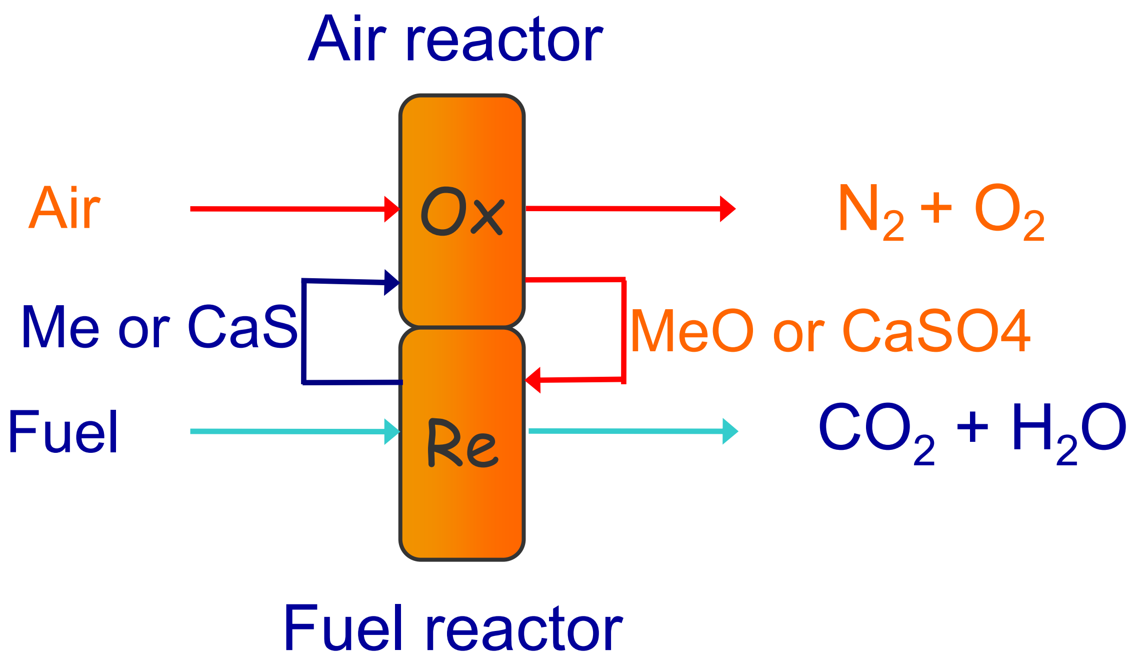
Oxy-Fuel Power Plant with Advanced O2 Production Technology

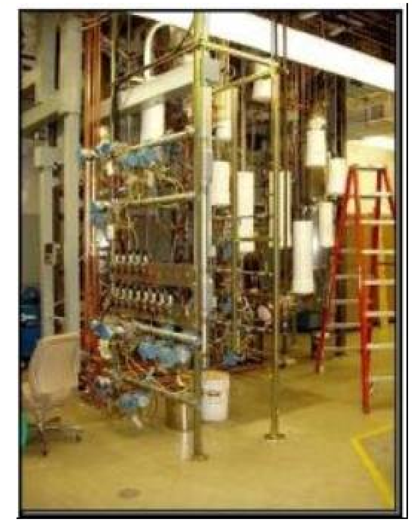


Breakthroughs will improve oxy-firing performance and economics

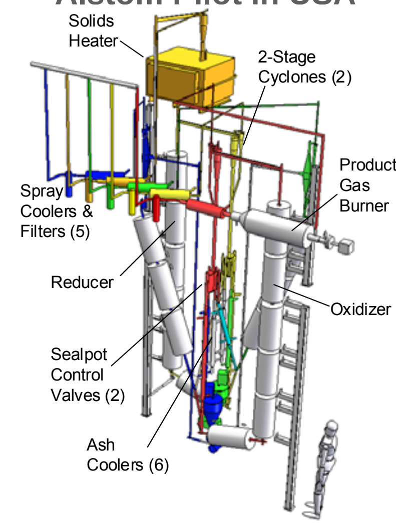
What is the status of developments?

Oxy-combustion: Chemical Looping Combustion (CLC)





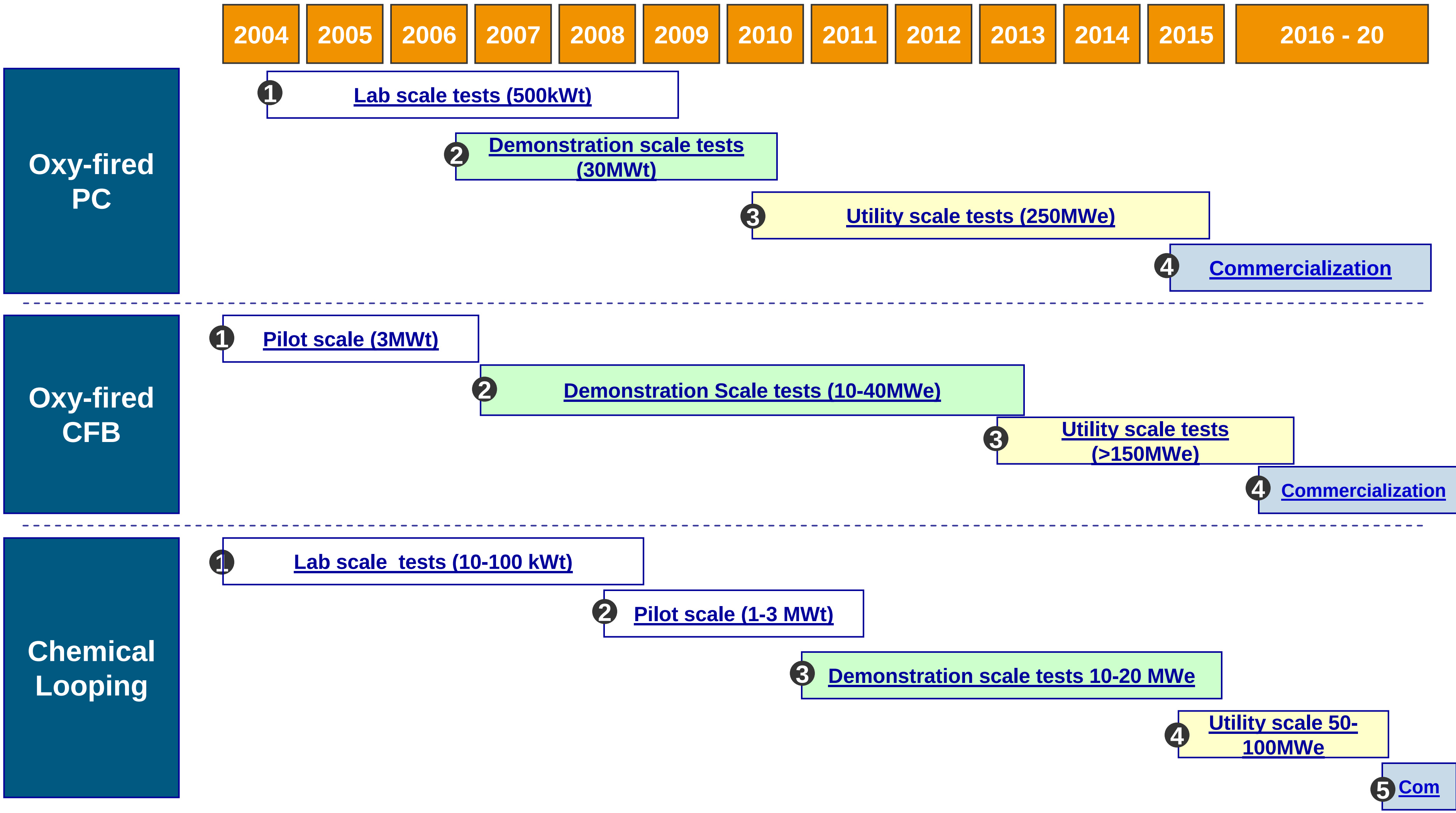
Alstom Pilot in USA



CLC features

- 100% CO2 Capture
- No Air Separation Unit
- Lowest Cost CO2 Capture
- High Net Plant Efficiency

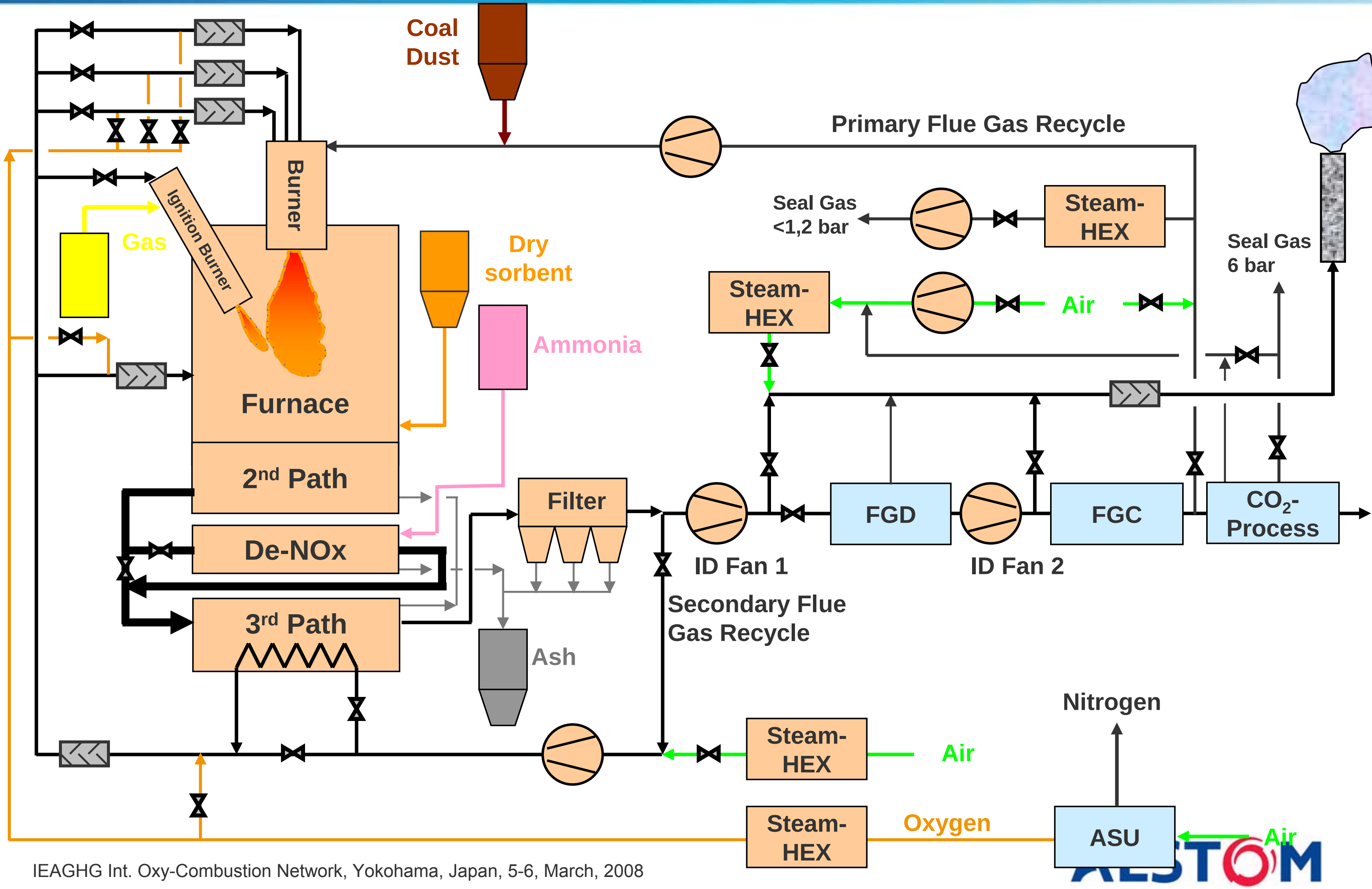
Long term products: Oxy-fired PC, Oxy-fired CFB and Chemical Looping



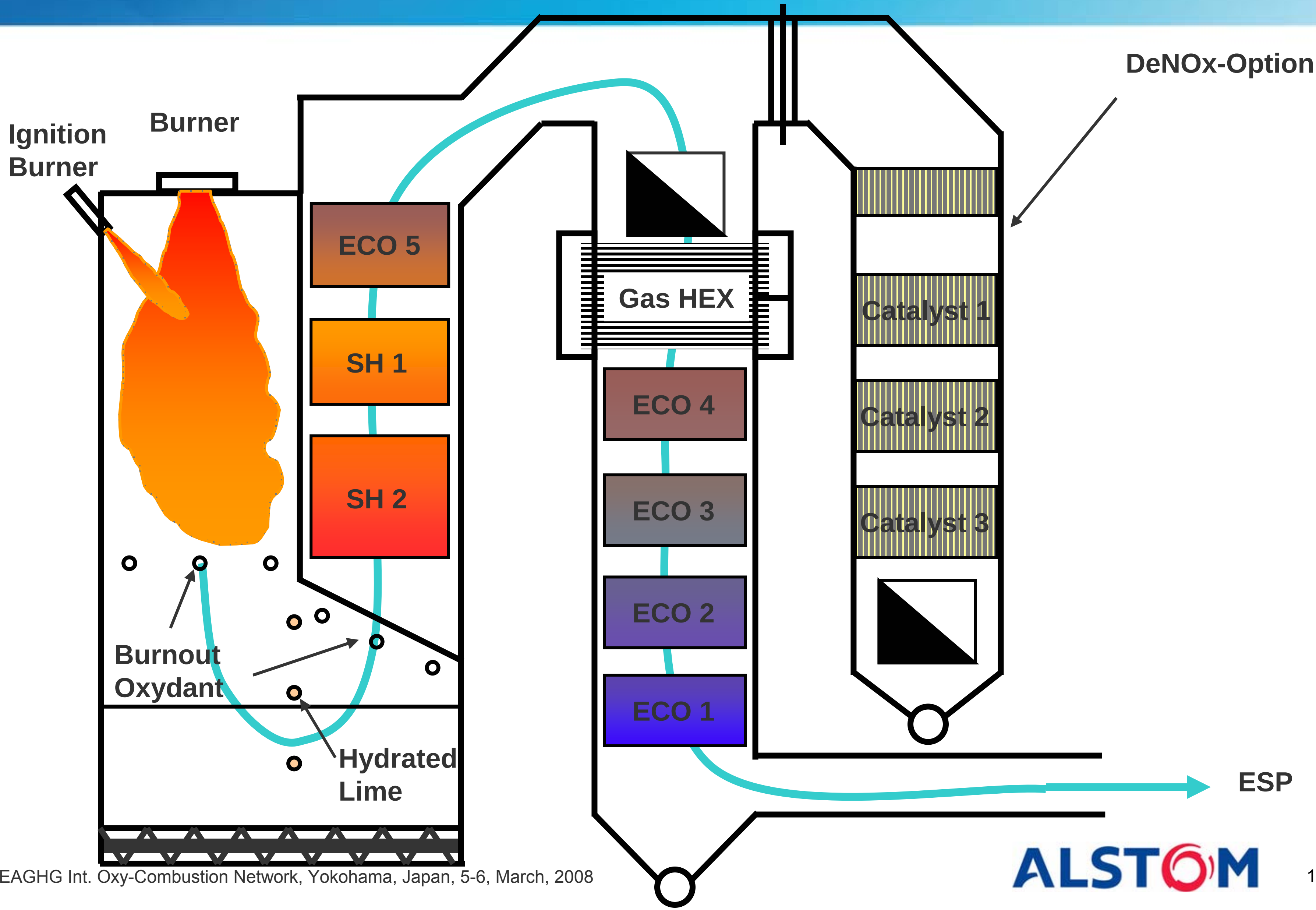
Source : ALSTOM analysis

30 MWth Oxyfuel Steam Generator – Vattenfall Schwarze Pumpe Site (Erection Status)

30 MWth Oxyfuel Steam Generator – Process

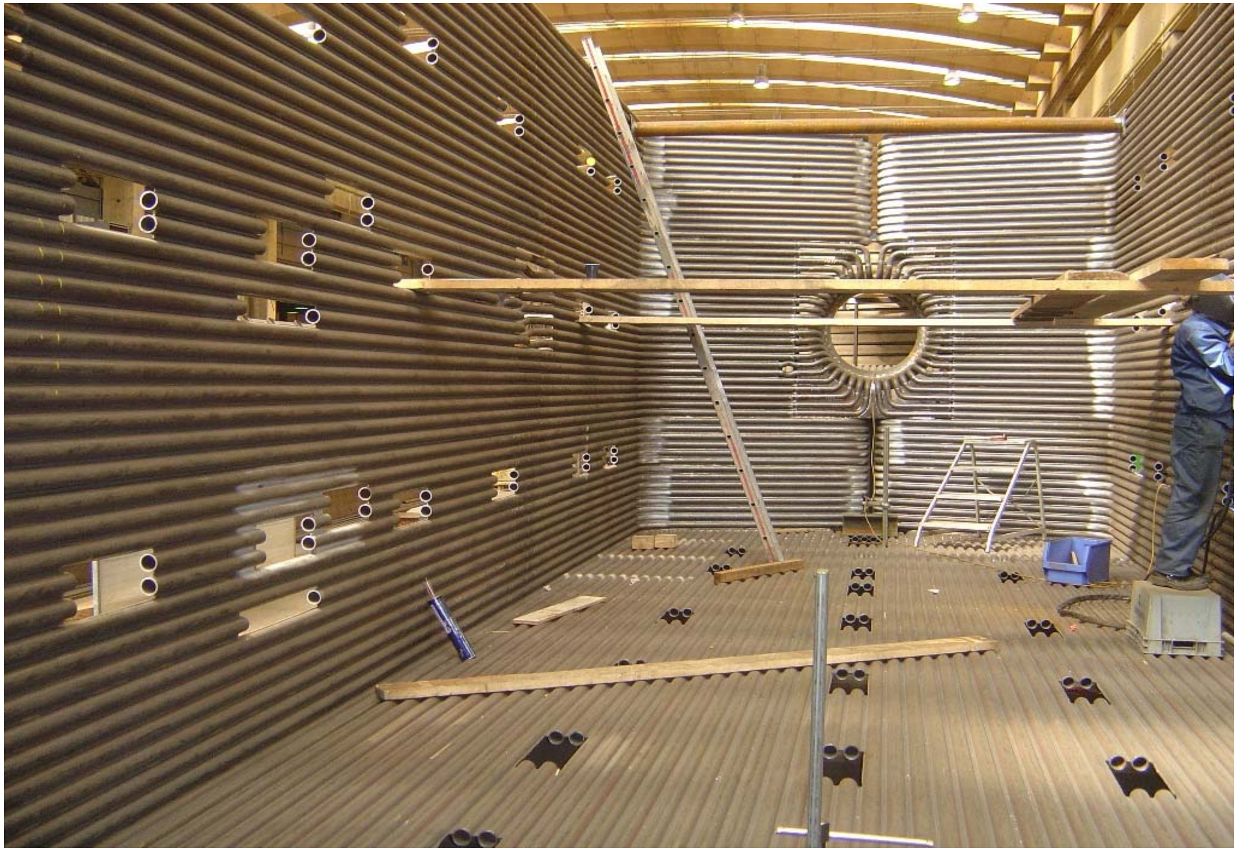


30 MWth Oxyfuel Steam Generator – Boiler Design



ALSTOM

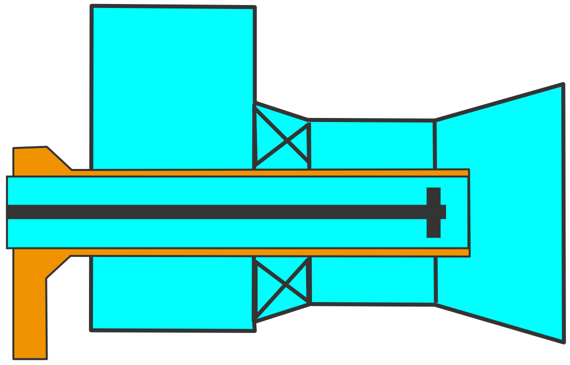
30 MWth Oxyfuel Steam Generator – Boiler Manufacturing



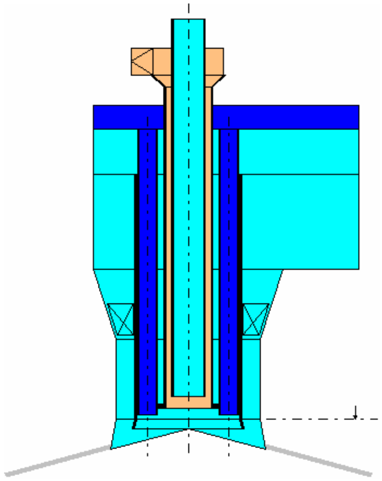
Sep. 2007

30 MWth Oxyfuel Steam Generator – Burner for Indirect Firing Systems

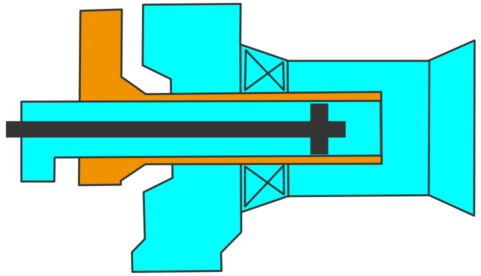
Niederaussem-K : 8 x 90 MW_{th}



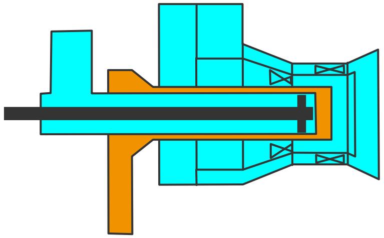
OxPP : 1 x 30 MW_{th}



ROW Wesseling K5 : 4 x 25 MW_{th}



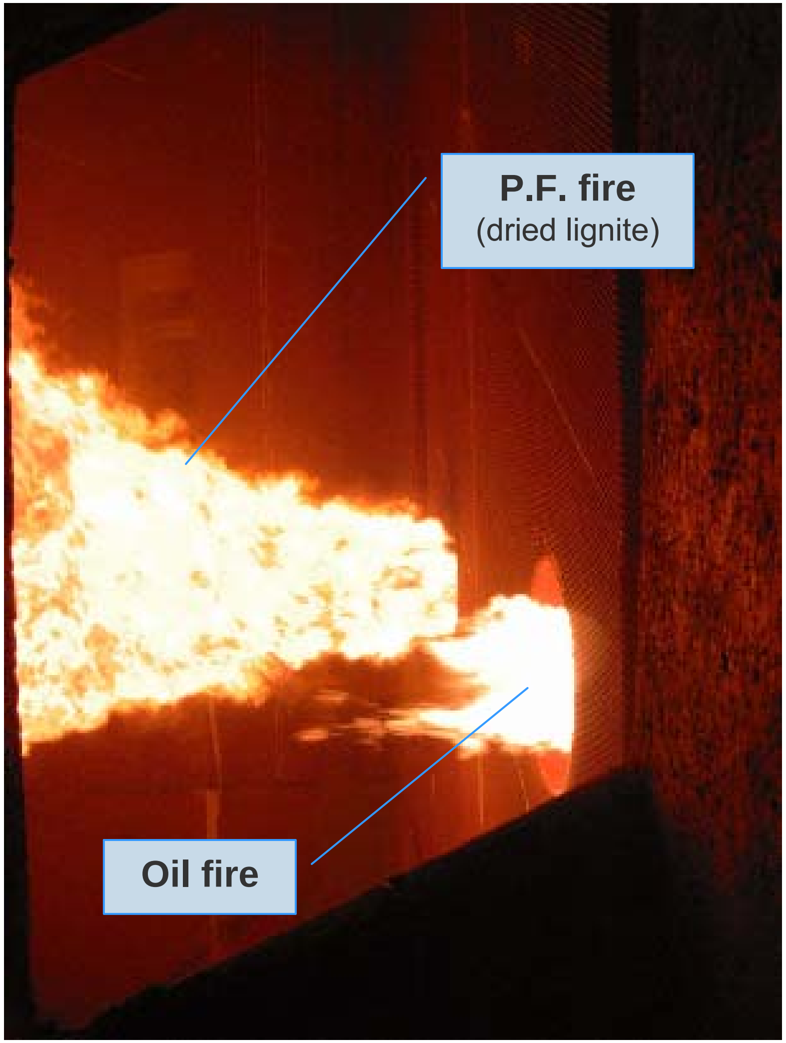
HKW Senftenberg : 2 x 19 MW_{th}



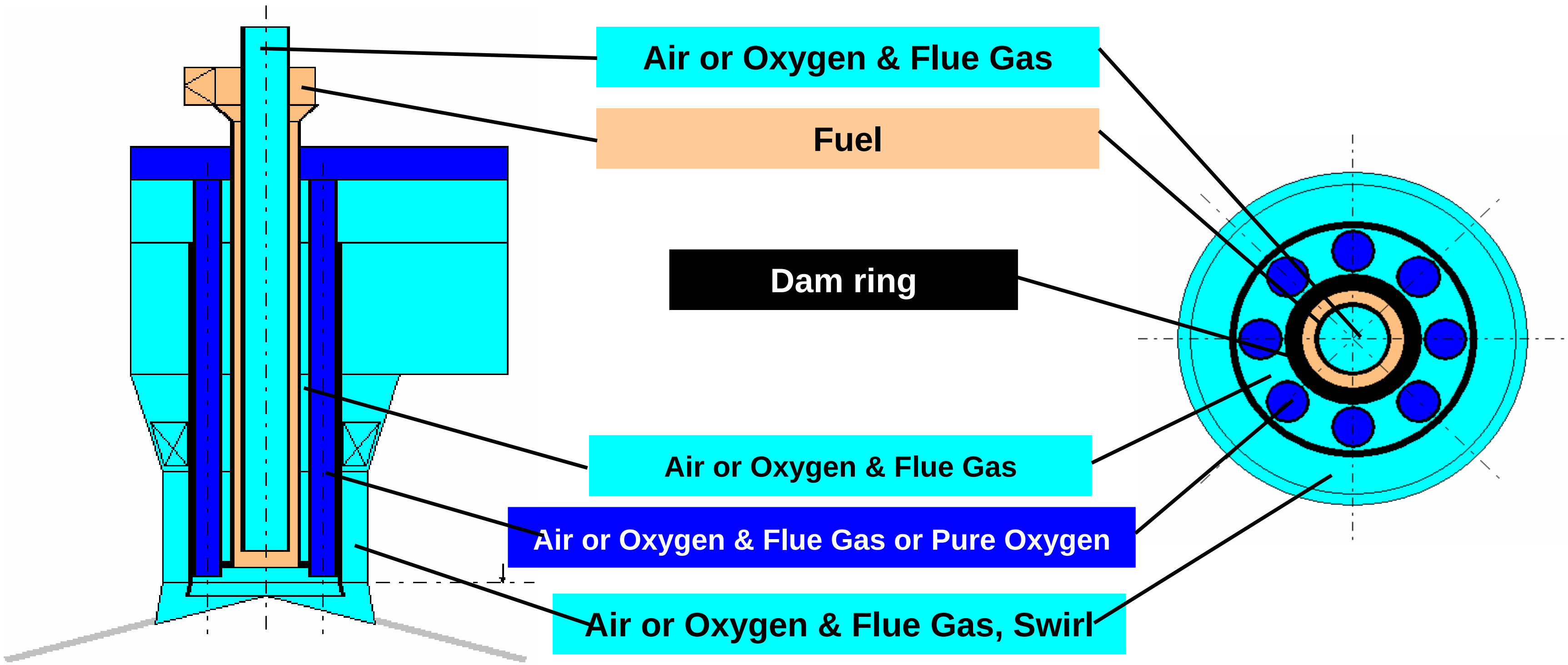
30 MWth Oxyfuel Steam Generator – Burner for Indirect Firing Systems (Reference Niederaussem K)

Niederaussem-K : 8 x 90 MW_{th}

- Since 2003 in operation
- Start up / Support firing system for a 1000 MW_{el} unit
- T-fired
- 8 burners installed
- Fuel : Dried Lignite ; 19,5 .. 21.7 MJ/kg
- Furnace Width : 23160 mm
- Furnace Depth : 23160 mm
- Oil gun



30 MWth Oxyfuel Steam Generator – Burner Design

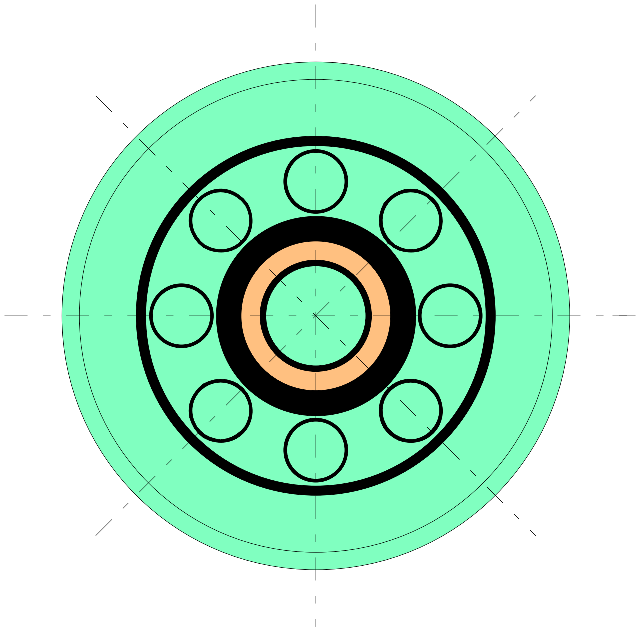


30 MWth Oxyfuel Steam Generator – Burner Operation Modes

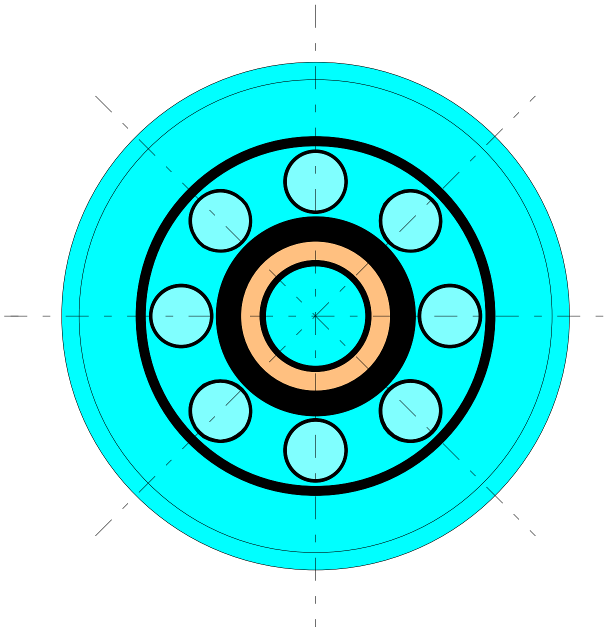
Green: Air
Brown: Fuel

Blue: RFG + O2
Brown: Fuel

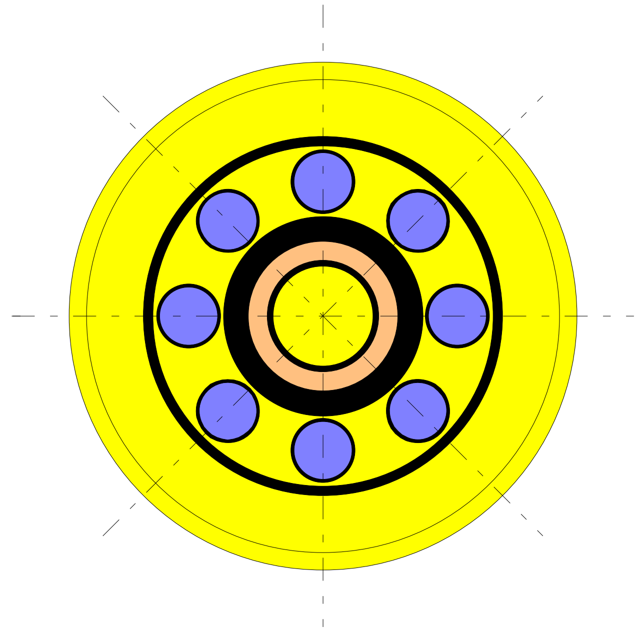
Yellow: RFG
Violet: O2
Brown: Fuel



Air operation



Oxyfuel operation
(premixed oxygen)



Oxyfuel operation
(direct oxygen injection)

Conclusions

- New coal fired power plants shall be designed for Highest Efficiency to minimize CO2 and other emissions
- Oxy-combustion is Complementary with conventional boiler and steam power plant technology, including efforts towards ultra-supercritical conditions (for Efficiency), and Environmental control developments
- Cost Attractive Options are needed and should be actively supported, particularly, breakthroughs like Chemical Looping & Adv. Oxygen
- Scale-up and Validation is needed
- The Schwarze Pumpe project is an important and significant demonstration. Start-up is expected this year

ALSTOM – The Clean Power Specialist

Today we provide the cleanest air solutions

- For New Plants
- For the Installed Base

Doosan Babcock Energy

Demonstration of an Oxyfuel Combustion System
Project Update

IEAGHG International Oxy-Combustion Workshop
3rd Workshop, 5th – 6th March 2008, Japan

E D Cameron and F D Fitzgerald

Date: 6th March 2008

Department: Research & Development

Doosan Babcock Energy Limited

- Doosan Babcock Energy Limited is a global, multi-specialist, energy services company, operating in the thermal power, nuclear, petrochemical, oil and gas and pharmaceutical industries
- Established in 1891 and headquartered in the UK, Doosan Babcock Energy Limited is a leading Original Equipment Manufacturer (OEM) of clean coal power plants and emission control technology
- In December 2006, Doosan Heavy Industries and Construction acquired Mitsui Babcock Energy Limited from Mitsui Engineering and Shipbuilding
- Doosan Heavy Industries & Construction forms part of the Doosan Group – one of the top 10 conglomerates in Korea - active in engineering, manufacturing and construction of power plants and industrial facilities worldwide
- Listed on the Korean Stock Exchange. Largest shareholder is Doosan Corporation

Doosan Babcock Energy Limited

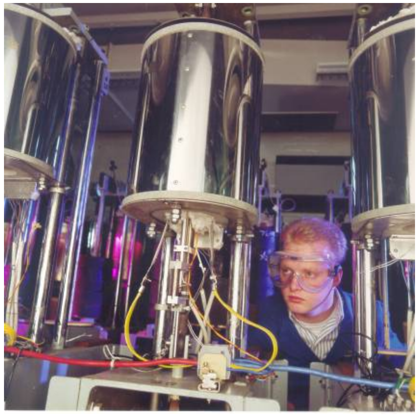
- Headquartered in Crawley, England, with main facilities in Renfrew, Scotland, and Branch offices throughout the UK
- FY 2007 annual order book £771 million (US$1500m approx)
- Employees 4,500 worldwide
- The only remaining UK based boiler OEM supplier
- Strong local aftermarket service capability and presence, combined with Engineer-Procure-Construct (EPC) capability
- Accreditations include:
  - ISO9001 : 2000 (Quality)
  - OHSAS 18001 (Health & Safety)
  - ISO14001 : 1996 (Environment)
- Dedicated to developing market leading technology through investment in people

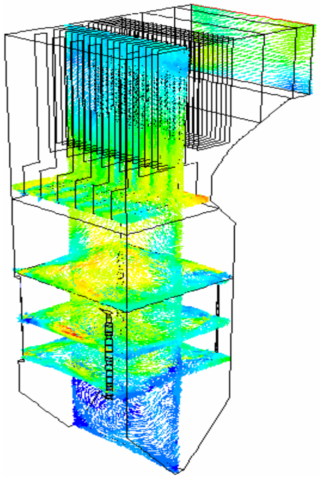
Research & Development

- Long tradition in R&D and technical support
- 250 multi-disciplinary scientists and engineers in purpose built building (2001)
- Specialised facilities and equipment
- Dedicated R&D Centre established July 07 growing from 50 to 200 staff.

R&D Areas:

- Boilers
- Combustion
- Materials and Fuels
- Software and Tools
- Asset Management





Oxyfuel Technology - Three Stage Development Programme

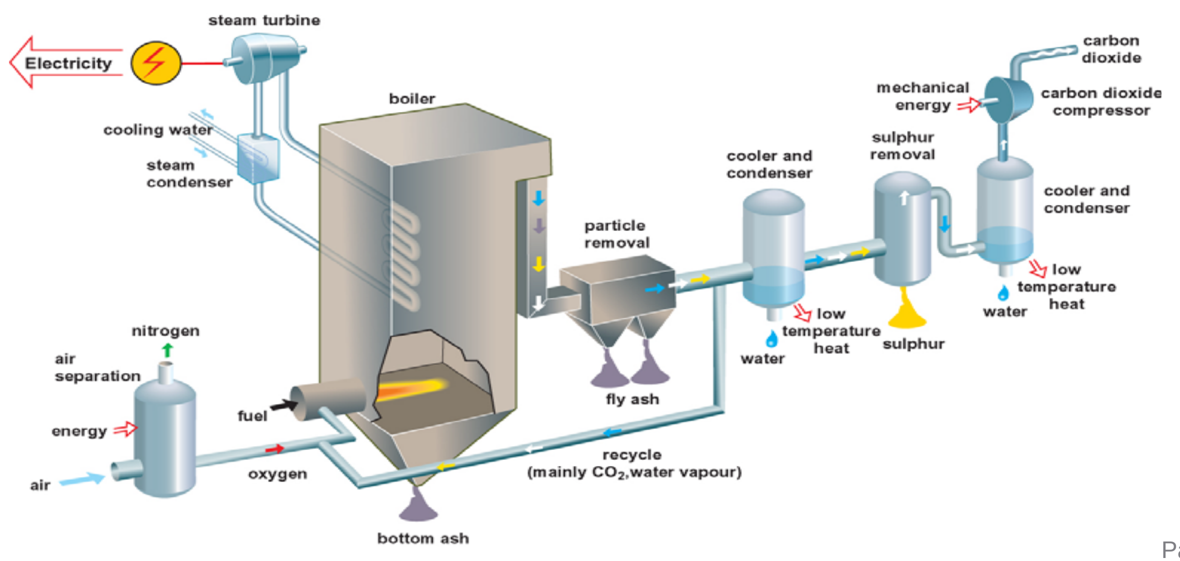
- To Develop a competitive Oxyfuel firing technology suitable for full plant application post-2010

- A phased approach to the development and demonstration of Oxyfuel technology:

  Phase 1: Fundamentals and Underpinning Technologies (2006 – 2008)

  Phase 2: Demonstration of an Oxyfuel Combustion System (2007 – 2009)

  Phase 3: Reference Designs (2009 – 2010)



1) **Combustion Fundamentals**

The tests, supported by TGA, microscopic, and elemental analysis, will establish the devolatilisation, char combustion, and nitrogen partitioning behaviour under air and oxyfuel firing conditions.

Drop tube furnace (DTF) characterisation of devolatilization, char burnout and nitrogen partitioning behaviour of six UK and world-trade coals under oxyfuel firing conditions.

First coal completed

Development of devolatilization and char burnout kinetic parameters from DTF data and application in CFD models of oxyfuel burner and oxyfuel boiler.

In progress

Explosion bomb characterisation of coal ignition behaviour under oxyfuel firing conditions (same coals as DTF tests).

In progress

1) **Combustion Fundamentals**

Preliminary test results show the following:

- The effect of CO_2 on coal devolatilisation was negligible at low temperatures (<1100°C) but became significant at higher temperature (1300°C). This may be indicative of some gasification of the coal. As expected, higher volatile yields were seen for the finer size fraction.

- Burnout varied dramatically with temperature (900-1300°C) and residence time (200-600 ms). Much higher levels of char burnout were achieved with an oxygen level of 10%, compared to 5%.

- Chars burned off quicker in CO_2 and the 75% CO_2/N_2 gas mix than in N_2 for both size fractions. However, the improvement in char burnout performance appeared to become less significant with increasing oxygen content. The promoting effect of CO_2 on char burnout was greater for the coarse char fraction.

Drop Tube Furnace testing and analysis of the other coals in the programme is ongoing at University of Nottingham

2) **Furnace Design & Operation**

To investigate the performance of the oxyfuel process and its key impacts on utility plant operation and performance.

Pilot scale testing (1MWt) of oxyfuel firing behaviour to two coals (parametric testing, fouling and corrosion behaviour).

First coal completed (as presented in Session 2b by B. Goh, E.On)

Characterisation of 1MWt test deposit samples by Computer Controlled Scanning Electron Microscope (CCSEM).

In progress

Laboratory-scale corrosion testing of candidate materials for final Superheater and Reheater sections of boiler under simulated oxyfuel flue gas.

First test completed

OxyCoal-UK : Phase 1 – Fundamentals and Underpinning Technologies

3) **Flue Gas Clean-up / Purification**
A numerical modelling study of AP's proposed CO_2 purification system will be undertaken, with particular emphasis on SO_x, NO_x, and Hg removal.

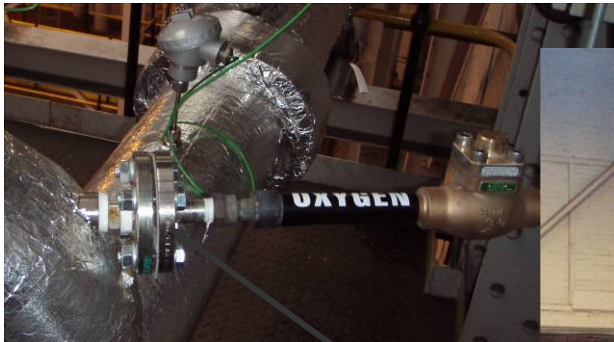
Conversion of 160kWt NO_x Reduction Test Facility (NRTF) to oxyfuel firing configuration.
Completed, Commissioning in Progress

Parametric testing of Oxyfuel Process.
Planned April 2008

Development and testing of novel flue gas clean-up / purification system using simulated and real oxyfuel flue gas.
Lab scale testing in Progress (as presented in Session 3 by V. White, Air Products)
Pilot scale testing planned April 2008

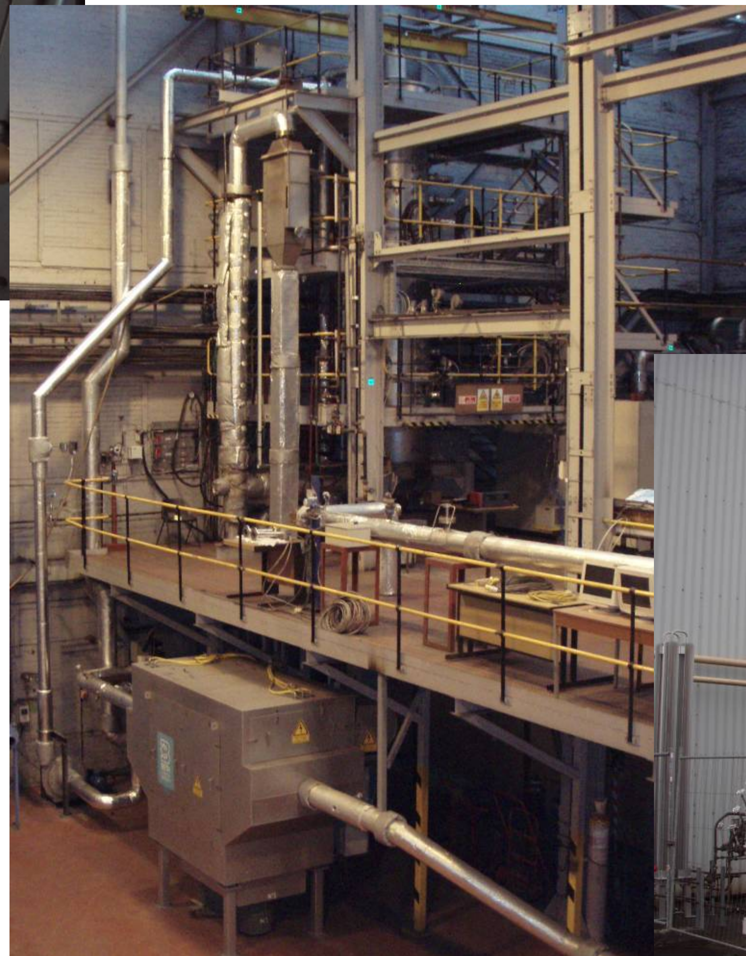
DOOSAN Doosan Babcock Energy

OxyCoal-UK : Phase 1 – Flue Gas Clean-up / Purification Progress



Oxygen Injection

Flue Gas Recycle Fan



Carbon Dioxide Storage

Oxygen Storage

OxyCoal-UK : Phase 1 – Fundamentals and Underpinning Technologies

4) **Generic Process Issues**
A desk-top study, supplemented by test results from the other project activities, will be undertaken to investigate the key process issues associated with an oxyfuel installation on a large utility plant.

Assessment of oxyfuel power plant reliability, availability, maintainability, operability and safety.

In progress

Front End Engineering Design (FEED) Study, including preliminary HAZOP study, for oxyfuel conversion of 90MWt Multi-fuel Burner Test Facility (MBTF)

Completed

OxyCoal-UK : Phase 1 – MBTF FEED Study Results

HAZOP Study Key Concerns

- Material compatibility in oxygen enriched atmospheres.
- Effect of fly ash on oxygen safety.
- Leaks of CO_2 rich flue gas from Flue Gas Recycle (FGR) ducts.
- FGR spray cooler effluent disposal.

HAZOP Study Actions

- Discussions regarding material compatibility continuing.
- FGR off-take located downstream of grit arrester rather than downstream of economiser to reduce FGR fly ash concentration.
- Primary FGR and Secondary FGR fans located as close to burner front as possible to minimise length of pressurised FGR duct.
- Primary FGR / Transport FGR spray cooler design(s) to minimise effluent acidity and discussions regarding appropriate disposal route.

OxyCoal-UK : Phase 2 – Demonstration of an Oxyfuel Combustion System

Project Aims:

- The aim of the project is to demonstrate an oxyfuel combustion system of a type and size (40MWt) applicable to new build and retrofit advanced supercritical oxyfuel plant.

- The specific objectives are:

  – Demonstrate successful performance of a full-scale (40MWt) oxyfuel burner firing at conditions pertinent to the application of an oxyfuel combustion process in a utility power generating plant.

  – Demonstrate performance of an oxyfuel burner with respect to flame stability, NOx, flame shape and heat transfer characteristics.

  – Demonstrate operational envelope of an oxyfuel burner with respect to flame stability, turndown, start-up shutdown and the transition between air- and oxyfuel-firing.

  – Demonstrate safe operation of an oxyfuel combustion process under realistic operating conditions.

  – Generate sufficient oxyfuel combustion process performance data to inform future investment decisions.

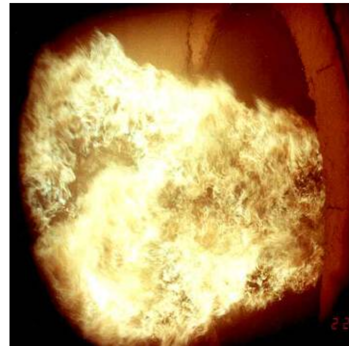
  – Demonstrate level of technology readiness of the oxyfuel combustion process.

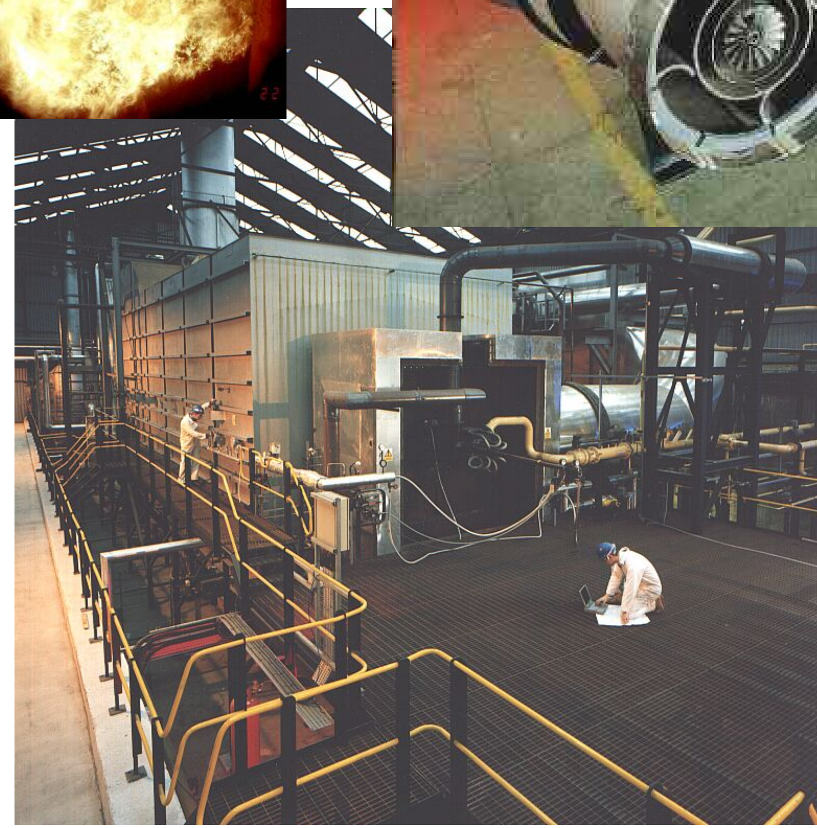
OxyCoal-UK : Phase 2 – Multi-Fuel Burner Test Facility (MBTF)

- **90 MW Thermal Input**

- **Capability to Fire a Wide Range of Fuels**
  - Coals, Bituminous and Low Volatiles
    - 8% to 40% Volatiles, Dry Ash Free
    - Up to 35% Ash, As Fired
    - Up to 20% Inherent Moisture, As Fired
  - Heavy Fuel Oil
  - Natural Gas
  - Orimulsion

- Facility usage:
  - New Burner Development
  - Contract burner testing
  - Third party burner testing





Task 1: Development of a Purpose-Designed Oxyfuel Demonstration Facility

Task 1.1: MBTF Oxyfuel Conversion Design

- Planning Approval
- Design (Process, Mechanical, Civil and EC&I)
- Safety
  - HAZOP Study
  - Risk Assessments
  - Work Instructions
  - Operating Procedures
  - Method Statements
  - COSHH Assessments
- Coal Characterisation by University of Nottingham

Task 1.2: MBTF Oxyfuel Conversion Installation

- Procurement
- Fabrication
- Installation

OxyCoal-UK : Phase 2 – Design Basis

• Design Coal:	Kellingley (UK Bituminous coal, 28%VM)
• Design Heat Input:	16, 28, 40, 49 and 70MW_t
• Flue Gas Recycle Rates:	50, 66 and 80%
• Excess Oxygen Range:	2 to 5% v/v (dry basis)

OxyCoal-UK : Phase 2 – Scope of Supply

- Retain air firing capability.

- Additional Equipment:
  - Flue Gas Recycle (FGR) Fans.
    - Transport FGR.
    - Primary FGR.
    - Secondary FGR.
  - Transport FGR Cooler/Condenser.
  - Primary FGR Cooler/Condenser.
  - Primary FGR Heater.
  - Oxygen Storage, Supply and Injection Systems for Primary and Secondary FGR.
  - Ductwork.
  - Isolating and Control Dampers.
  - E, C & I, including Burner Management and SCADA System, Modifications.

OxyCoal-UK : Phase 2 – Task 2 and 3

Task 2: Finalising of Burner Design and Manufacture

Task 2.1: Oxyfuel Burner Design and Fabrication

- First generation oxyfuel burner design based on Doosan Babcock's expertise and experience in air firing technology for coal

Task 2.2: MBTF Oxyfuel Conversion Commissioning

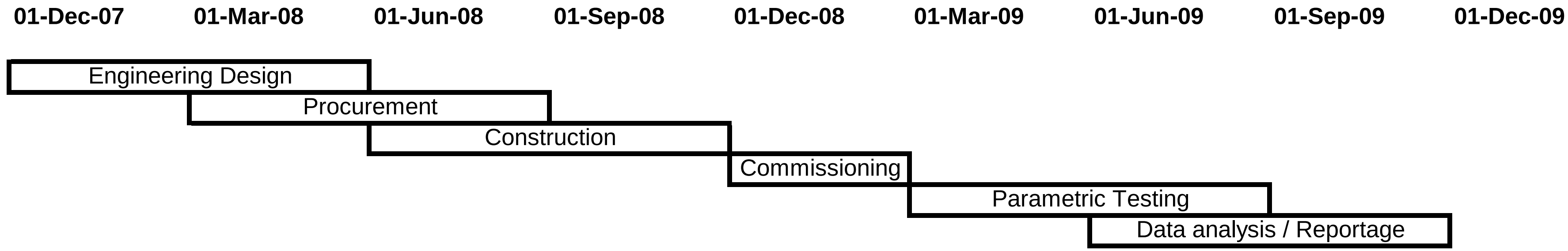
- Cold commissioning
- Hot commissioning

Task 3: Demonstration of an Oxyfuel Combustion System

- Establish operational envelope of the burner and performance characteristics of the combustion process. Key parameters to be investigated include:
  - Change-over from air to oxyfuel firing at various loads.
  - Turndown.
  - Flame stability.
  - Heat release and heat flux to furnace walls.
  - Pollutant emissions.
  - Flame visualisation by Imperial College London

OxyCoal-UK : Phase 2 – Progress

- Project Start: 1st December 2007

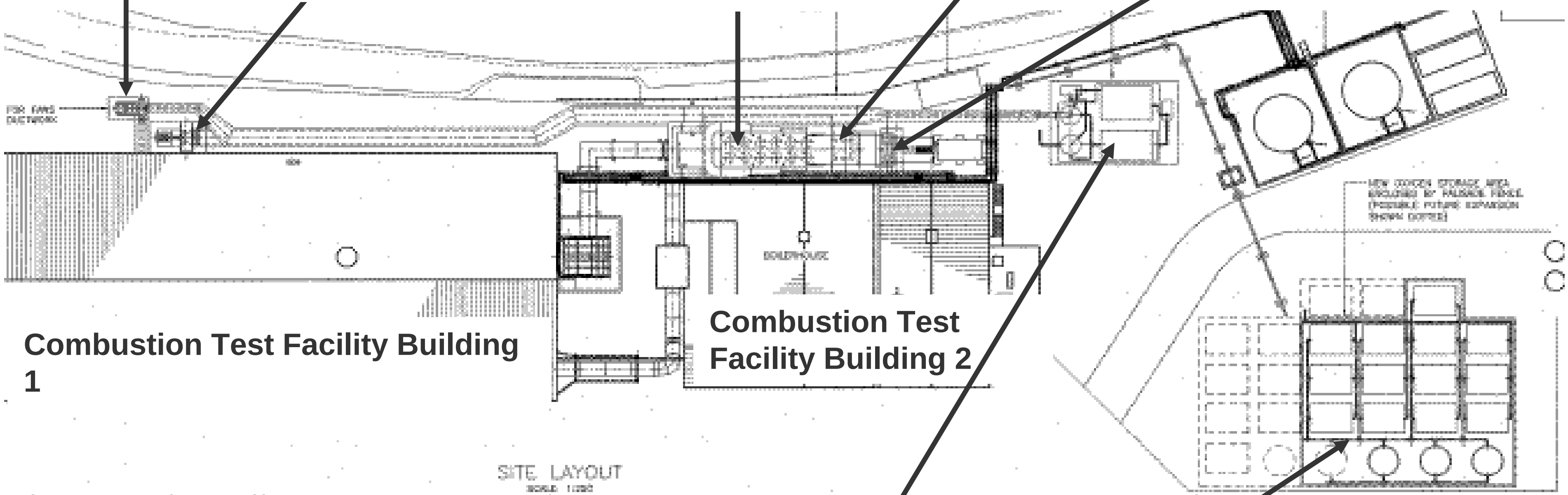


- Planning application submitted

- Initiation Scottish Environmental Protection Agency (SEPA) Variation application

- Design in progress – all disciplines
  - Site Layout
  - PFD
  - Duct and fan sizing
  - Oxygen plant
  - Civils
  - Power supply requirements
  - P&ID

OxyCoal-UK : Phase 2 – Planned Layout



Doosan Babcock Energy

Concluding Remarks

Phase 1

- Investigate Combustion Fundamentals, Furnace Design & Operation, Flue Gas Clean-up / Purification and Generic issues associated with Oxyfuel Process
  - Lab and Pilot Scale test data being produced and under going analysis
  - Safety issues associated with Oxyfuel Process identified

Phase 2

- Full Scale component test ready for application on Full Plant Demonstration

The current tasks complete the foundation for the development of an oxyfuel boiler reference design

OxyCoal-UK : Phase 1 – Project Participants

Lead company

Doosan Babcock Energy Limited

Industrial Participants

Air Products plc

BP

E.ON UK Limited

RWE

University Participants

Imperial College London

University of Nottingham

Sponsors / Sponsor Participants

Scottish and Southern Energy

Scottish Power

EdF Energy

Drax Power Limited

Dong Energy Generation A/S

Government Support

Department of Business, Enterprise and Regulatory Reform

Technology Strategy Board

OxyCoal-UK : Phase 2 – Project Participants

Lead company

Doosan Babcock Energy Limited

University Participants

Imperial College London

University of Nottingham

Prime Sponsor

Scottish and Southern Energy

Sponsors

Air Products plc

Dong Energy Generation A/S

Drax Power Limited

EdF Energy

E.ON UK Limited

Scottish Power

Government Support

Department of Business, Enterprise and Regulatory Reform

HFCCAT Demonstration Programme

Thank you for your attention

Contact details:

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3rd Workshop

IEAGHG Oxy Fuel Network

Yokohama, Japan

March 5th and 6th 2008

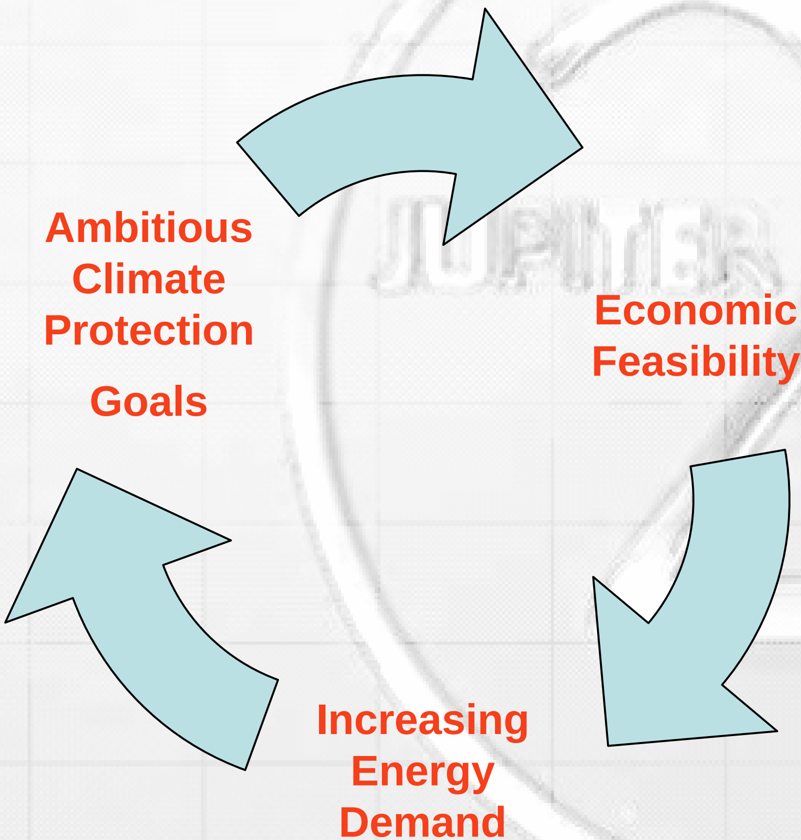
Brian R. Patrick

Director of Development

Jupiter Oxygen Corporation (USA)

www.jupiteroxygen.com

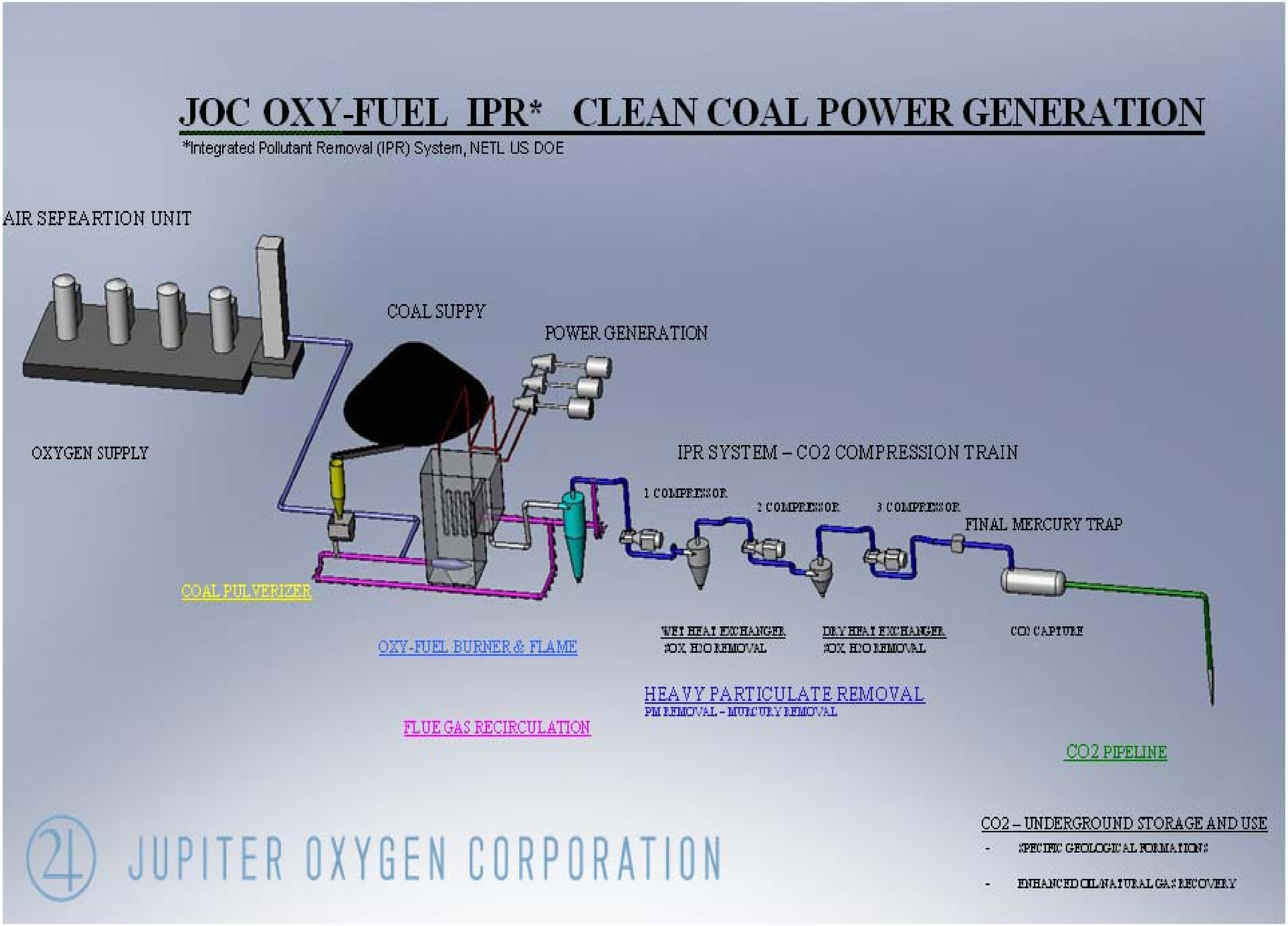
Keys for Carbon Capture Technology



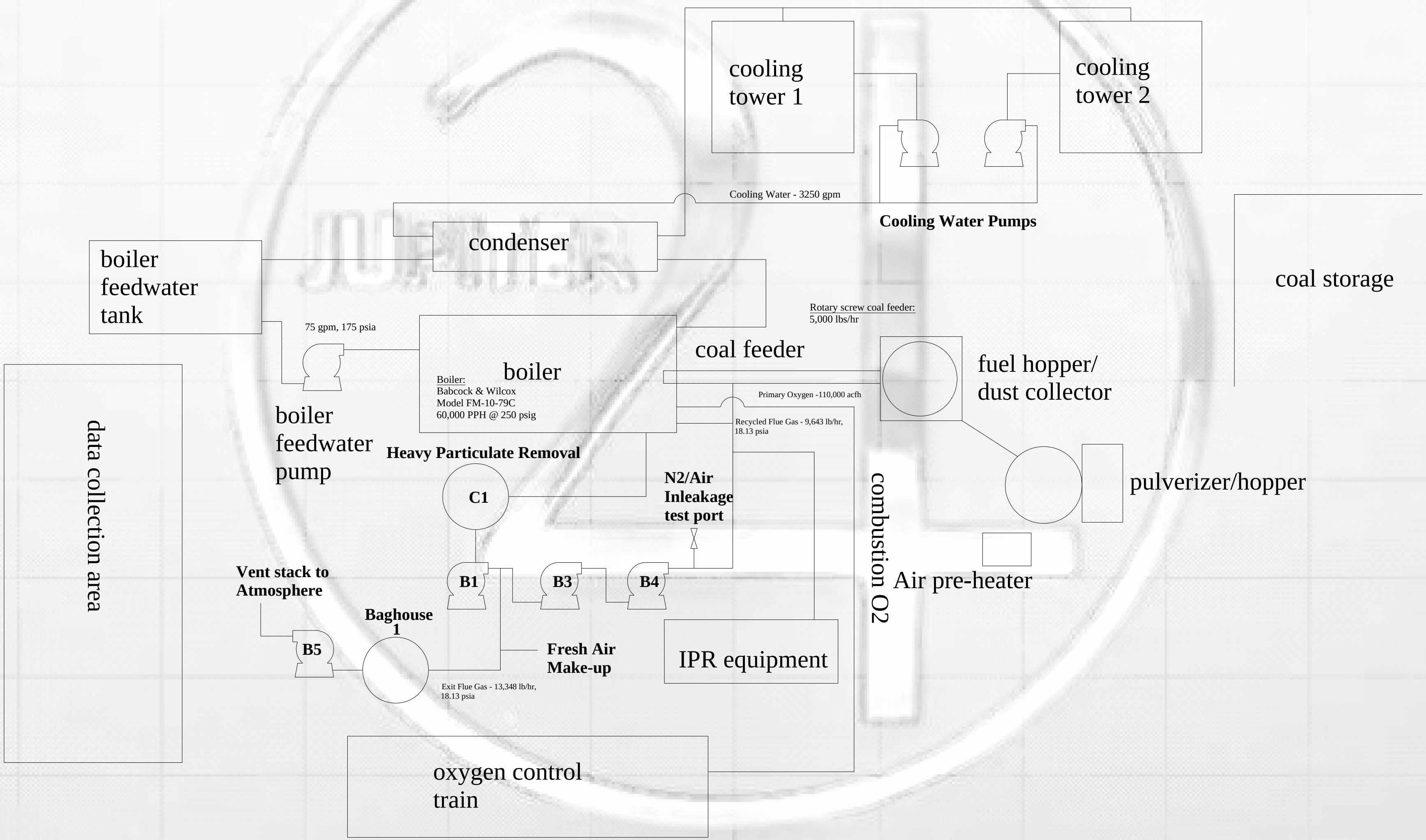
→ Key for successful carbon capture technology development:

- Reduce parasitic power losses associated with carbon capture
- Use cost effective technology for carbon capture
- Create a practical approach for retrofits
- Design a truly CO2 capture ready concept

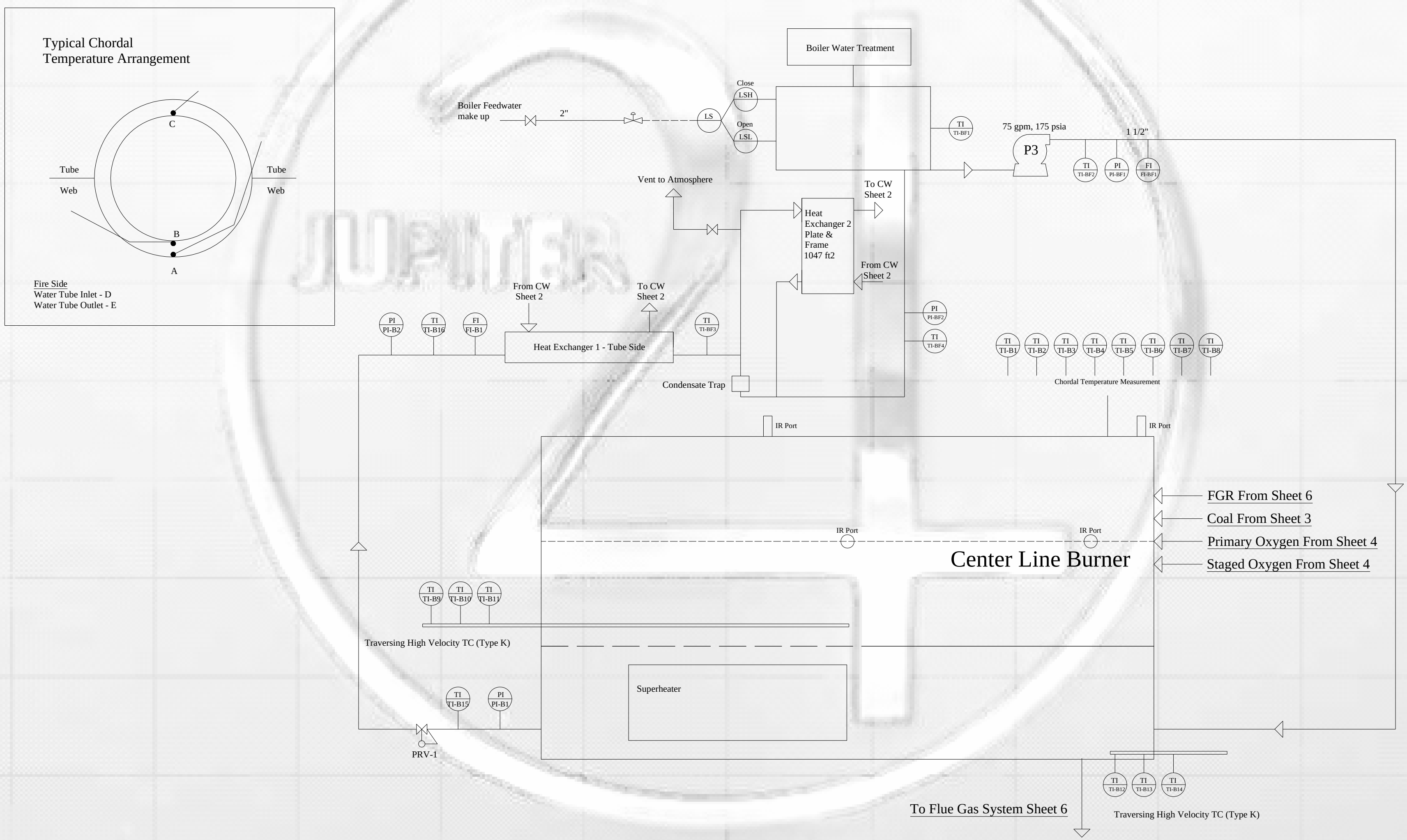
Jupiter Oxygen – Hammond Indiana 15 MWth Test Facility


JOC OXY-FUEL IPR* CLEAN COAL POWER GENERATION
*Integrated Pollutant Removal (IPR) System, NETL US DOE
AIR SEPEARTION UNIT
COAL SUPPY
POWER GENERATION
OXYGEN SUPPLY
IPR SYSTEM – CO2 COMPRESSION TRAIN
1 COMPRESSOR
2 COMPRESSOR
3 COMPRESSOR
FINAL MERCURY TRAP
COAL PULVERIZER
OXY-FUEL BURNER & FLAME
WET HEAT EXCHANGER
SOX, H2O REMOVAL
DRY HEAT EXCHANGER
SOX, H2O REMOVAL
CO2 CAPTURE
HEAVY PARTICULATE REMOVAL
PM REMOVAL – MURCURY REMOVAL
FLUE GAS RECIRCULATION
CO2 PIPELINE
CO2 – UNDERGROUND STORAGE AND USE
- SPECIFIC GEOLOGICAL FORMATIONS
- ENHANCED OIL/NATURAL GAS RECOVERY
JUPITER OXYGEN CORPORATION

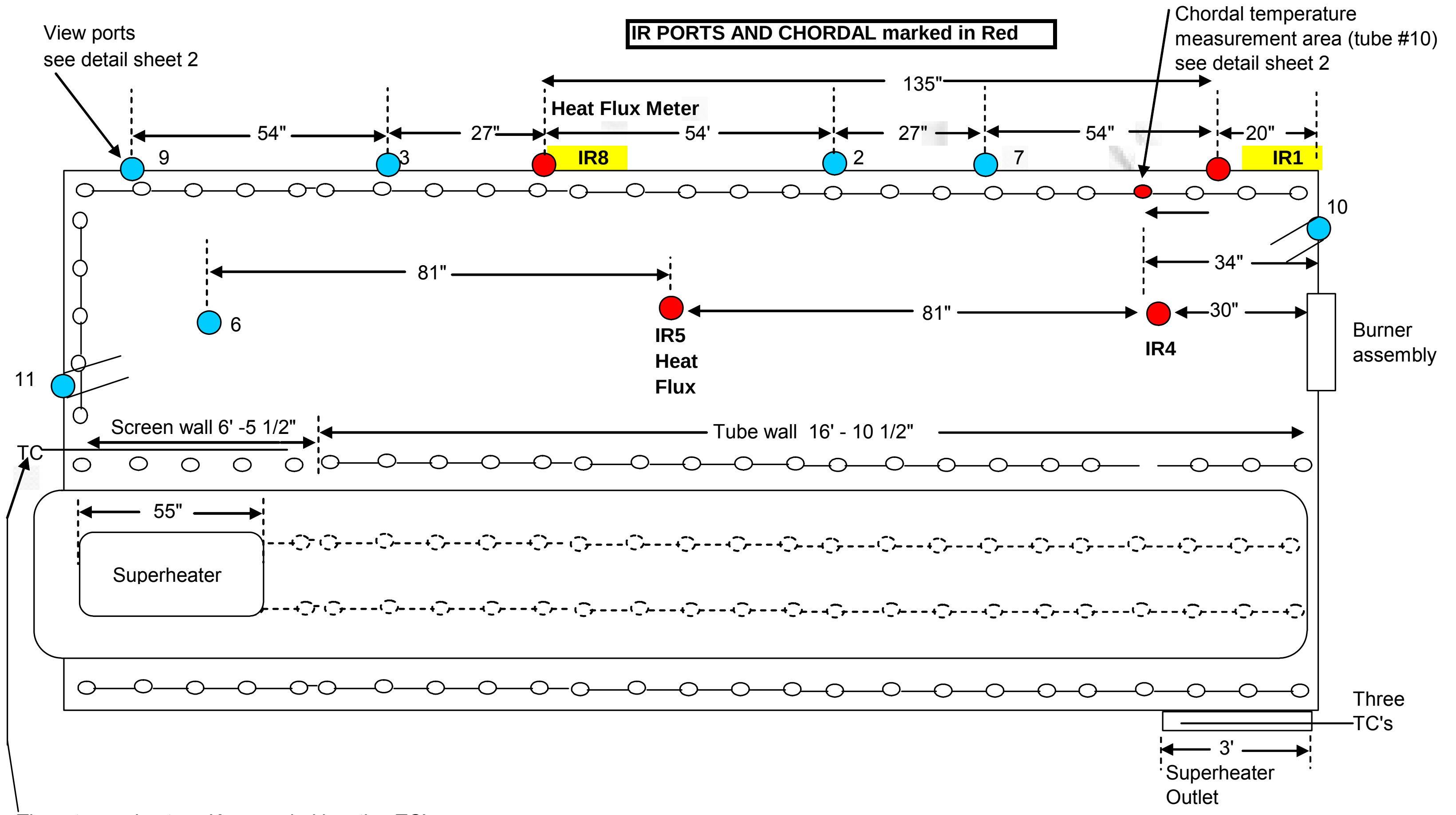
15 MWth Oxy-Fuel Test Facility - Hammond, Indiana



Boiler PID Loop

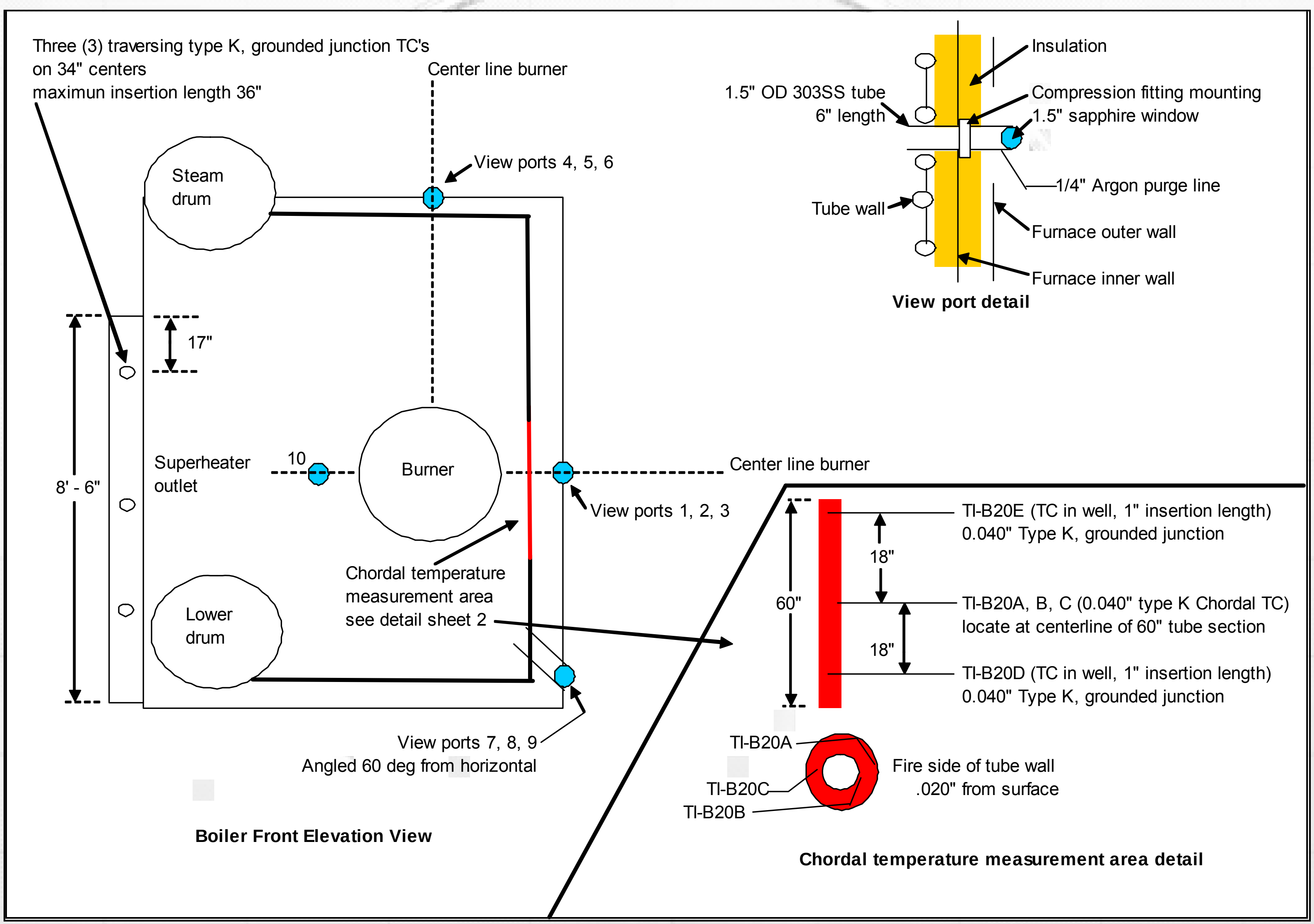


15 MWth Boiler Plan View

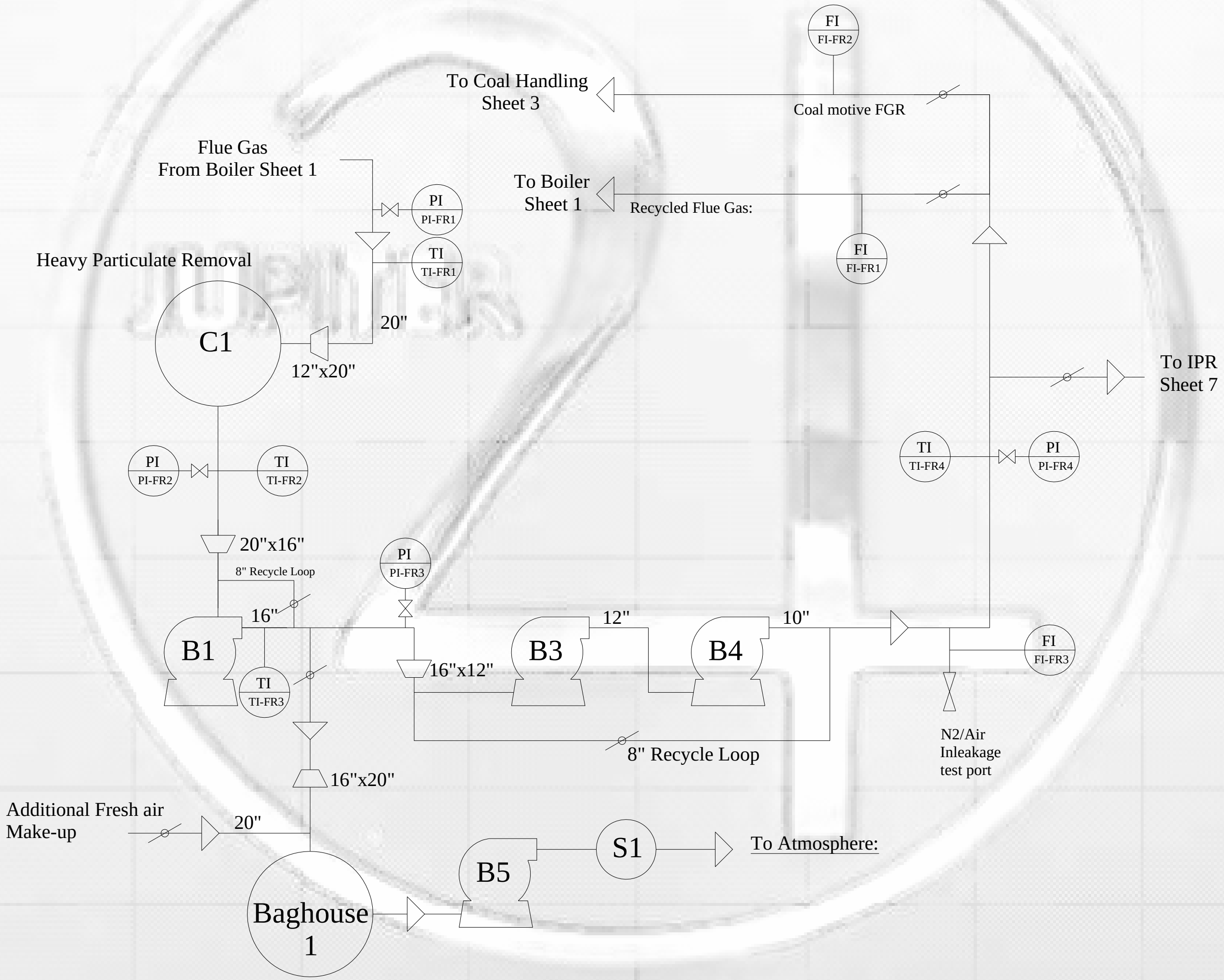


Boiler Plan View

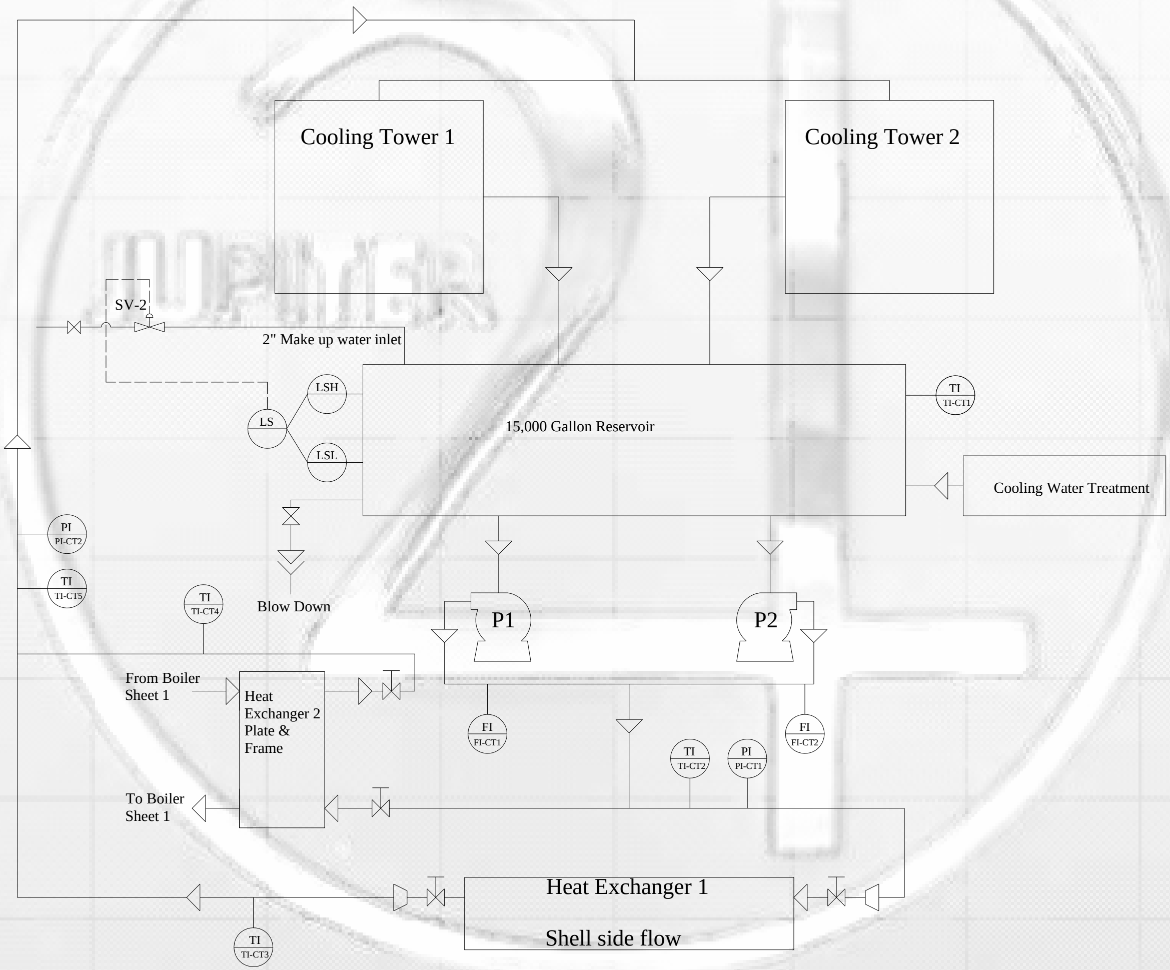
15 MWth Boiler Front View



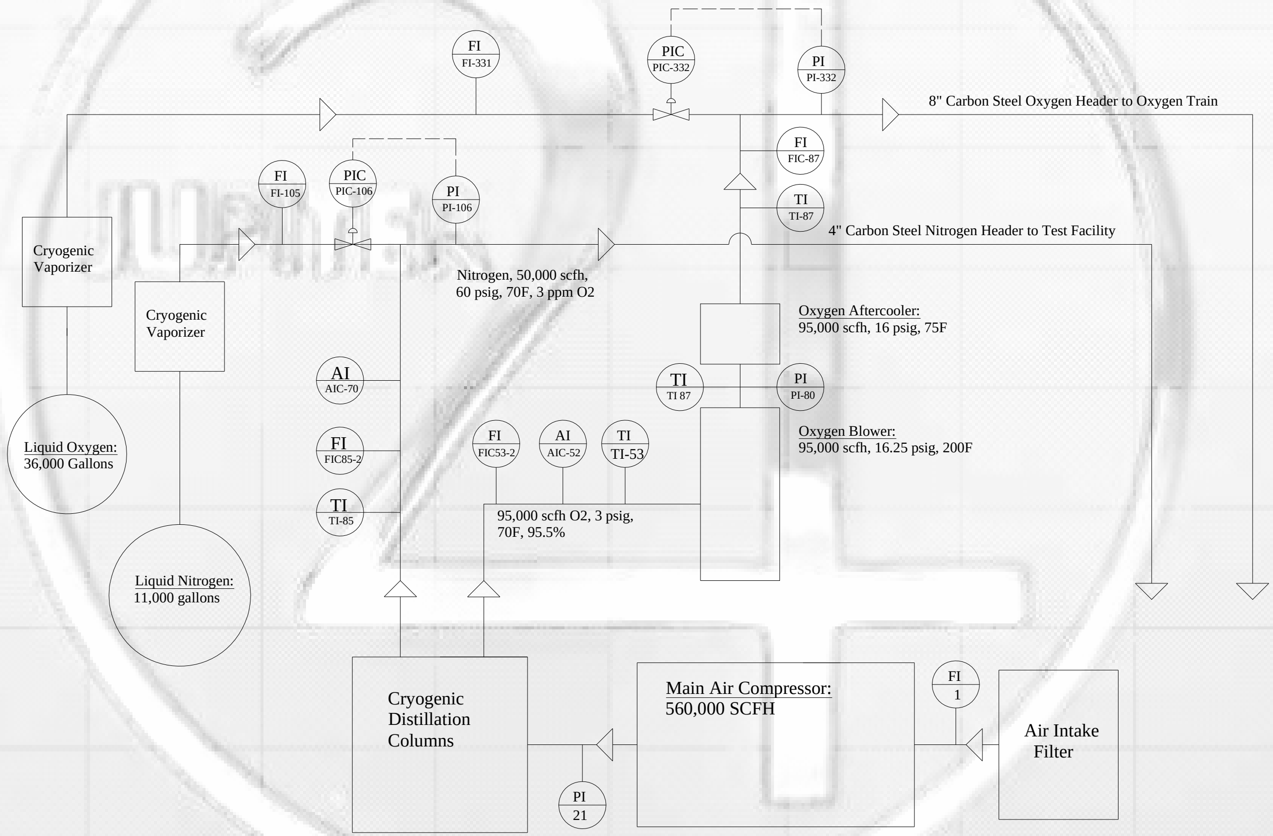
Flue Gas Recirculation



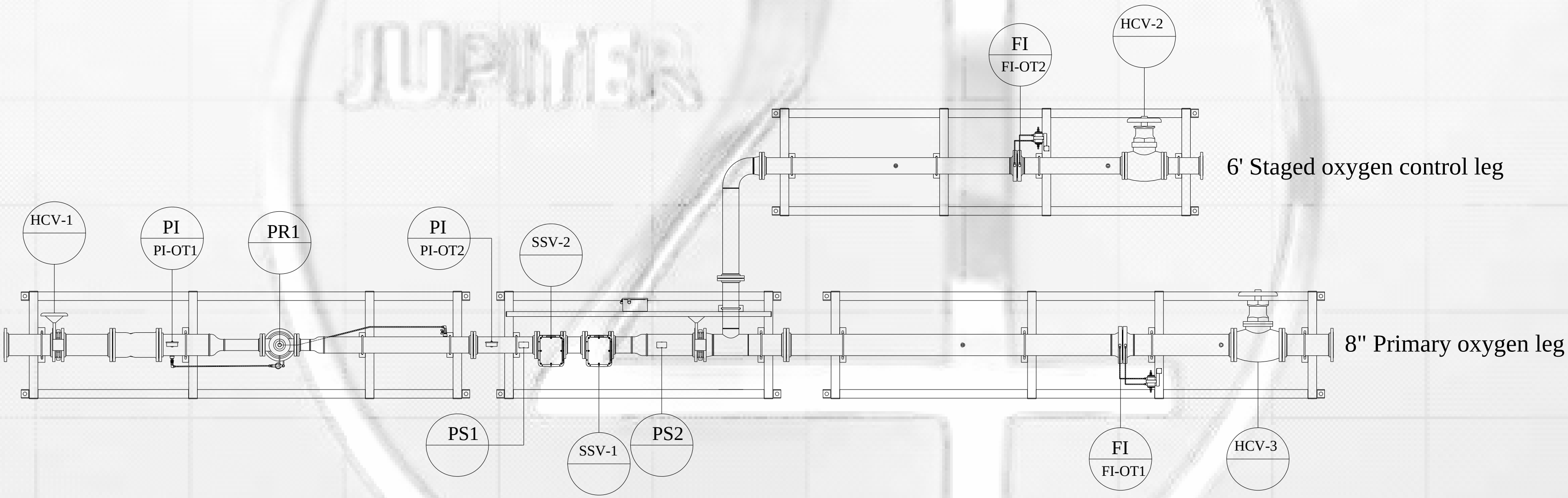
Cooling Tower Loop



105 TPD Cryogenic Plant

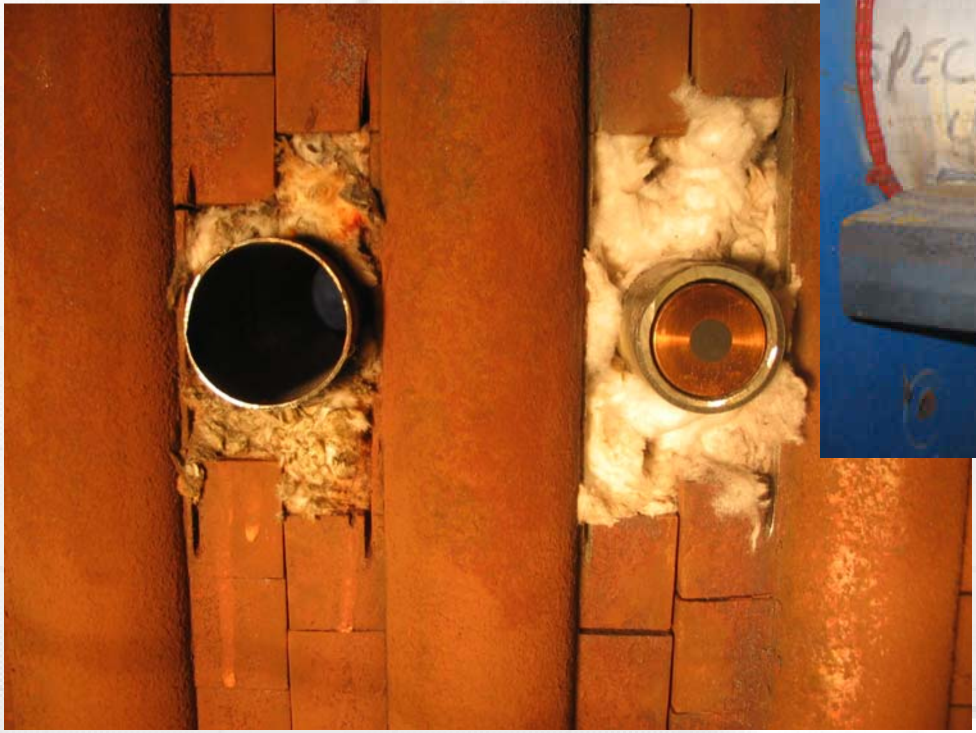


Oxygen Control



15 MWth Test Facility

Heat Transfer



Project Participants

- Jupiter Oxygen
  - Construction of the test facility
  - Operation of the test facility
  - Technology provider for the Oxy-fuel
- Doosan Babcock LLC
  - Part of the data evaluation team
  - Slagging and fouling studies
- USDOE – National Energy Technology Laboratory
  - Integrated Pollutant Removal System
  - Data Collection design
  - Materials analysis
  - Final fate analysis
  - CO2 Quality
- Maxon Corporation
  - Supplier of oxy-fuel burner
  - Supplier of oxygen control systems
- Coalteck LLC
  - Consultant power generation
- Michigan State
  - High Temperature oxygen sensor
  - Material coupon analysis
- Purdue University
  - Heat Transfer Radiant versus Convective
  - Thermal Transfer modeling
  - Data reduction and Analysis
- University of Wyoming
  - Study on recycle with Wyoming coals

- **WEB:**
- www.jupiteroxygen.com

- **CONTACT US:**

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- **PHONE**: 219 712 5206   **FAX**: 847 928 0795
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- **PHONE:** 219 746 5586   **FAX**: 847 928 0795
- **EMAIL**: b_patrick@jupiteroxygen.com

Session 7 Panel Discussion

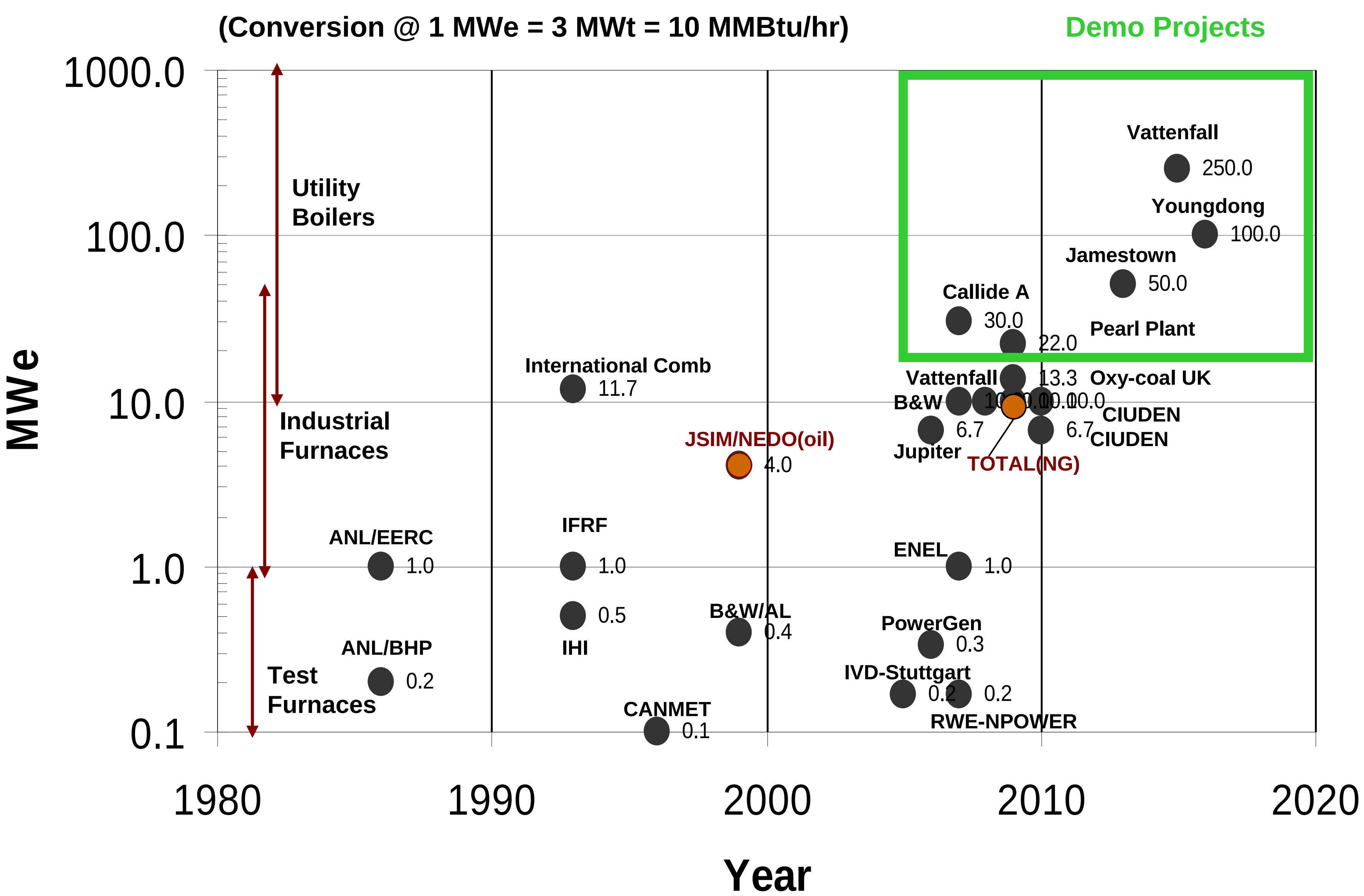
Large Scale Pilot and Demo Projects

Chairperson	**Dr. H. Sho Kobayashi**	**Praxair**
Panel Members		
	Dr. Marie Anheden	**Vattenfall**
	Dr. Frank Kluger	**Alstom**
	Dr. Chris Spero	**CS Energy**
	Dr. Claude Prevende	**TOTAL**
	Prof. Vicente Cortes-Galeano	**CIUDEN**
	Prof. Sangmin Choi	**KAIST**
	Dr. Minish Shah	**Praxair**
	Dr. Horst Hack	**Foster-Wheeler**

Large Scale Pilot and Demo Projects

PROJECT	**Location**	**MWt**	**Start up**	**Boiler Type**	**Main Fuel**	**CO2 Train**
B & W	USA	30	2007	Pilot PC	Bit, Sub B., Lig.	
Jupiter	USA	20	2007	Industr. No FGR	NG, Coal	
Oxy-coal UK	UK	40	2008	Pilot PC		
Vattenfall	Germany	30	2008	Pilot PC	Lignite (Bit.)	**With CCS**
Total, Lacq	France	30	2009	Industrial	Nat gas	**With CCS**
Pearl Plant	USA	66	2009	22 MWe PC	Bit	Side stream
Callide	Australia	90	2010	30 MWe PC	Bit.	**With CCS**
Ciuden - PC	Spain	20	2010	Pilot PC	Anthra.(Pet ck)	?
Ciuden - CFB	Spain	30	2010	Pilot CFB	Anthra.(Pet ck)	?
Jamestown	USA	150	2013	50 MWe CFB	Bit.	**With CCS**
Vattenfall	Germany?	~1000	2015	~250 MWe?	Lignite (Bit.)	?
Youngdong	Korea	~400	2016?	~100 MWe PC?	?	?

Oxy-Fuel Combustion Boiler Projects



Callide Oxyfuel Project
Technical evaluation of oxy-combustion and CO2 capture system

IEAGHG International Oxy-Combustion Network

Yokohama, Japan

5 & 6 March 2008

C Spero (CS Energy)

T Yamada (IHI Corporation)

E Sturm (Air Liquide Engineering)

D McGregor (GLP Engineering)

Callide Oxyfuel Project

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generations ahead

Presentation content

- Project overview
- Process description
- Evaluation of stack emissions
- Construction program update

The purpose of this presentation is two-fold:

1. To share technical data on the project; and
2. To highlight some of the practical considerations associated with an oxyfuel retrofit

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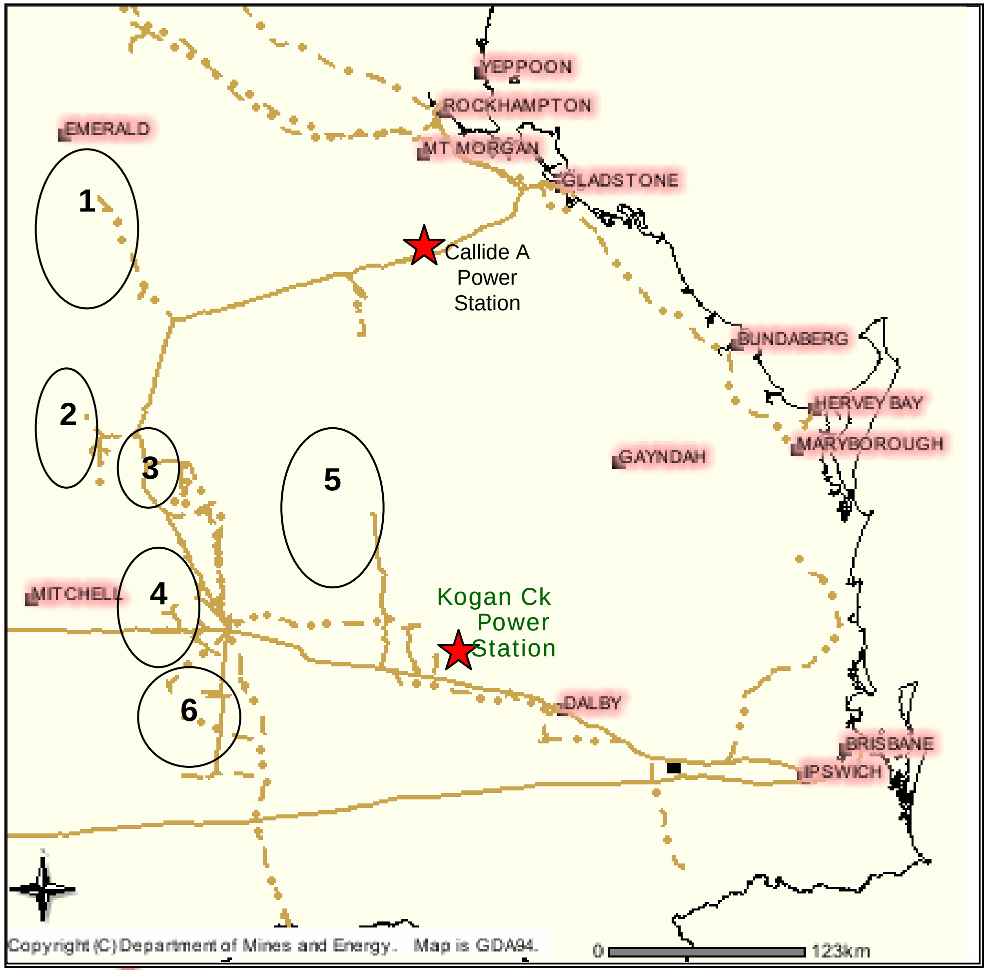
Project location



Callide A Power Station
4 x 30 MWe
Steam 130 t/h at 4.1MPa, 460°C
Commissioned: 1965 – 69
Refurbished 1997/98

CO_2 storage areas:

1. Northern Denison Trough
2. Southern Denison Trough
3. Fairview CSM Field
4. Roma Shelf
5. Burunga/Wandoan Anticlines (CSM)
6. Wunger Ridge

Gas & Oil Pipelines

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Project participants

Participants:

- CS Energy (QLD Government)
- Xstrata Coal
- Australian Coal Association - ACALET
- Japanese Partnership (IHI, J-Power, Mitsui & Co.)
- JCOAL – Supporting Collaborator
- Schlumberger

Other:

- Commonwealth Government (LETDF Program)
- METI (Japanese Government)

Plant suppliers

- Air separation unit (ASU) and CO2 compression and purification unit (CPU), design & equipment supply – Air Liquide Engineering
- ASU & CPU construction – GLP Engineering
- Boiler retrofit design & equipment supply – IHI
- Boiler retrofit construction - CBH

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Callide oxyfuel project

Scope:

4 Yr project duration

Boiler refurb.

2 x 330 TPD ASU

Oxy-comb. Retrofit

75 TPD CO2 recovery

Trucking to CO2 reservoir

Injection and monitoring (50kt)

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Boiler parameters

Coal		
Total moisture	%	12 - 16
Ash	%, as-received	19 - 24
Gross calorific value	MJ/kg, as-received	18 - 20.5
Greenhouse emission factor	kg CO2/MWh	1.9 - 1.95
Steam @ maximum continuous rating		
Mass flow (design)	kg/h	136,080
Peak rating (design)	kg/h	149,688
Pressure	kPa(a)	4,410
Temperature	^{o} C	463
Unit conditions		
Rating	MWe	30
Coal flow @ MCR	kg/h	18,300 - 21,000
Flue gas flow @ MCR	kg/h	158,000 - 165,000
Typical steam condition:	115,920 kg/h, 4160 kPa(a) and 465^{o}C	

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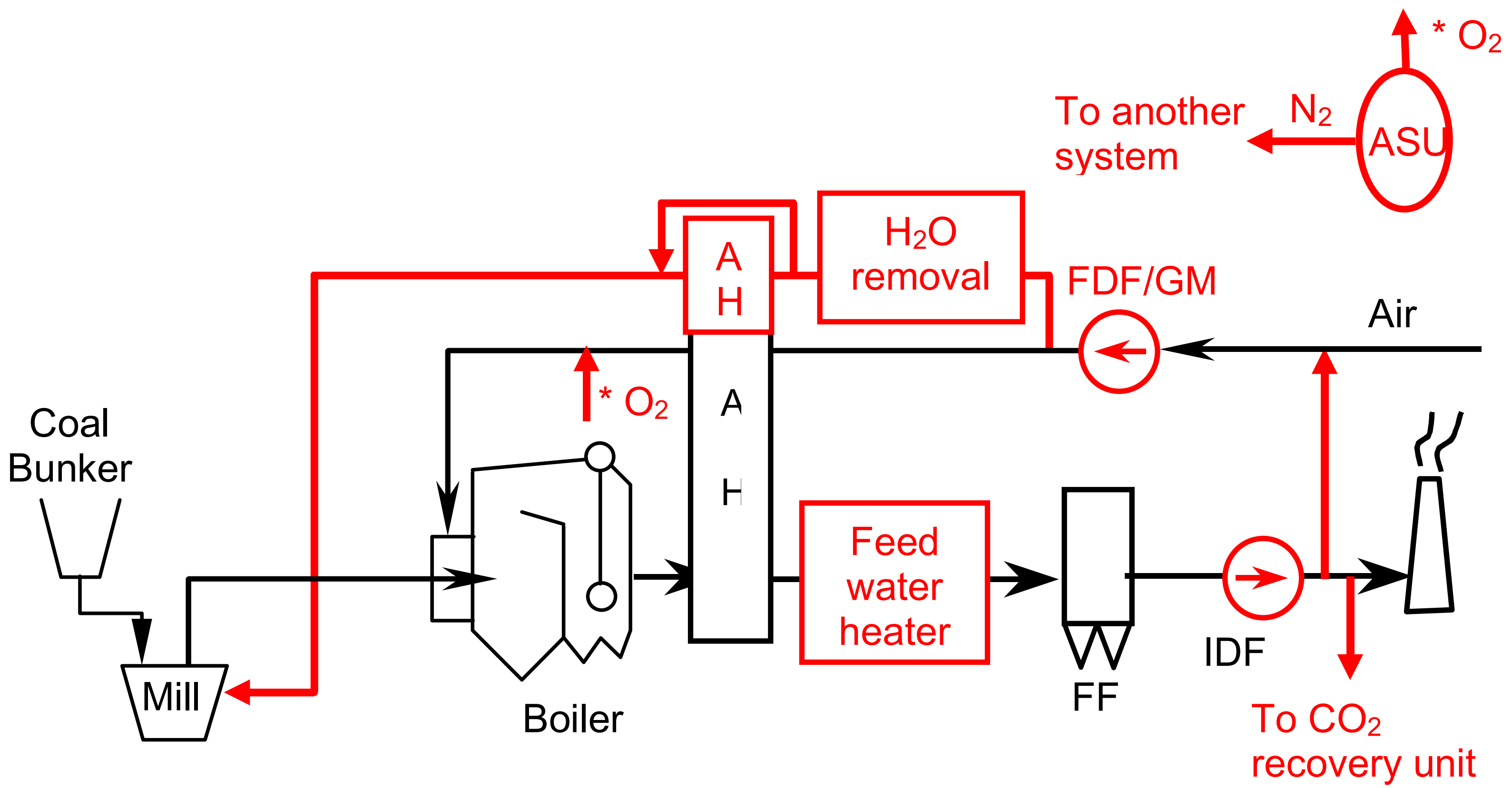
Retrofit flowchart

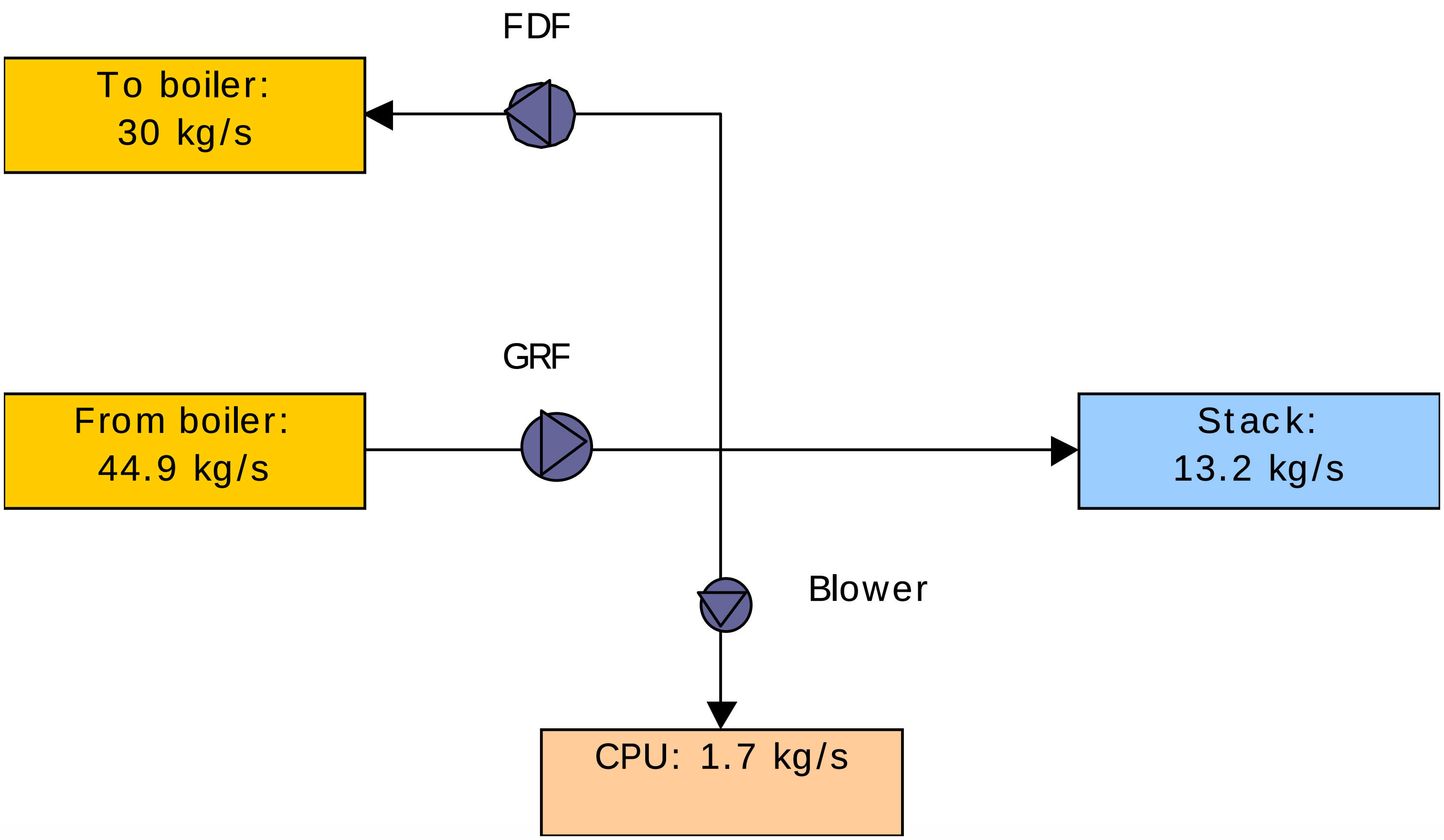


Oxygen supply

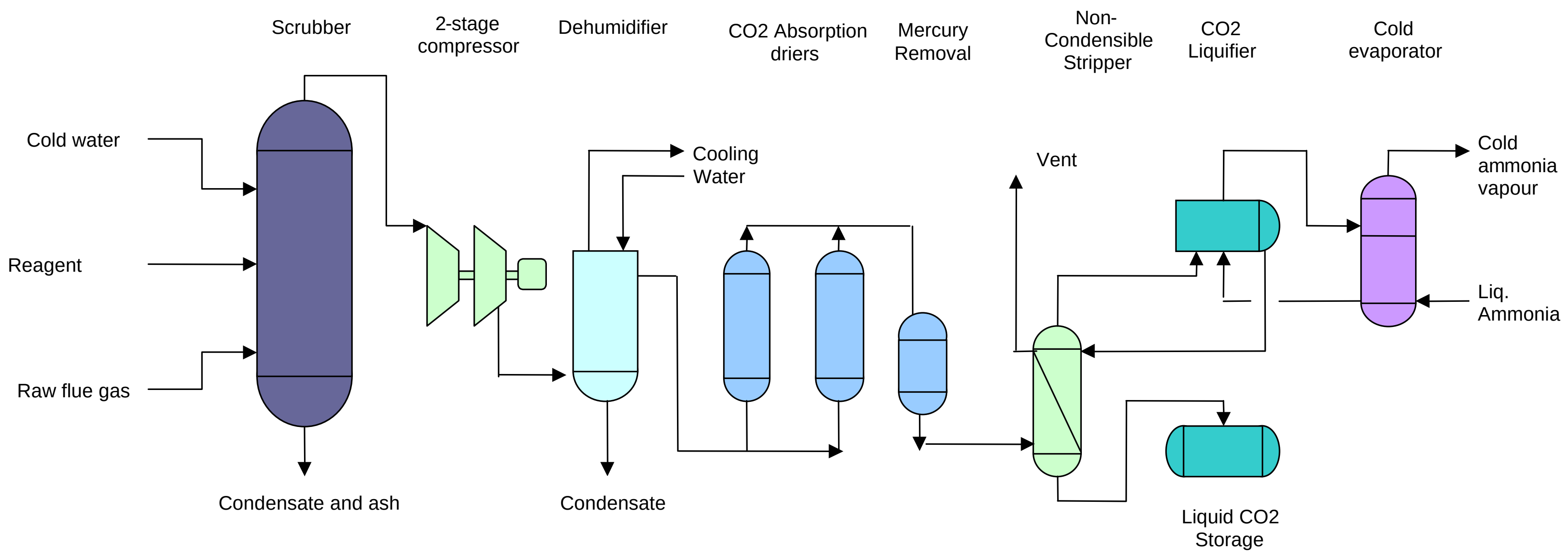
2 x nominal 330 TPD Air Liquide Sigma cryogenic ASUs

Parameter	Unit	Value
O2 production	t/day	660
Product flow rate	Nm3/h	19,200
	kg/h	27,430
Delivery pressure	kPa(a)	180
O2 purity	vol. %	98

Flue gas mass balance



CO2 compression & purification plant (CPU): Flowchart



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CO_2 compression & purification plant (CPU): Inputs & outputs

75 t/day liquid product

Parameter	Units	CPU Inlet	CO2 Product
Flow rate	kg/s	1.3	0.9
	Am3/s	1.7	
Temperature	°C	145	-30
Pressure	kPa (a)	101	1600
Composition			
H_2O	mole %	20.0	< 0.002
O_2	mole %	4.2	< 0.003
N_2 (+ Ar)	mole %	18.6	< 0.1
CO_2	mole %	55.9	99.9
SO_2	mole %	0.06	< 0.003
NOx	mole %	0.03	< 0.003
Particulate	mg/Nm3	< 100	< 1
Trace elements (As, Be, Cd, Hg, V)	ppbv	< 1	< 0.1

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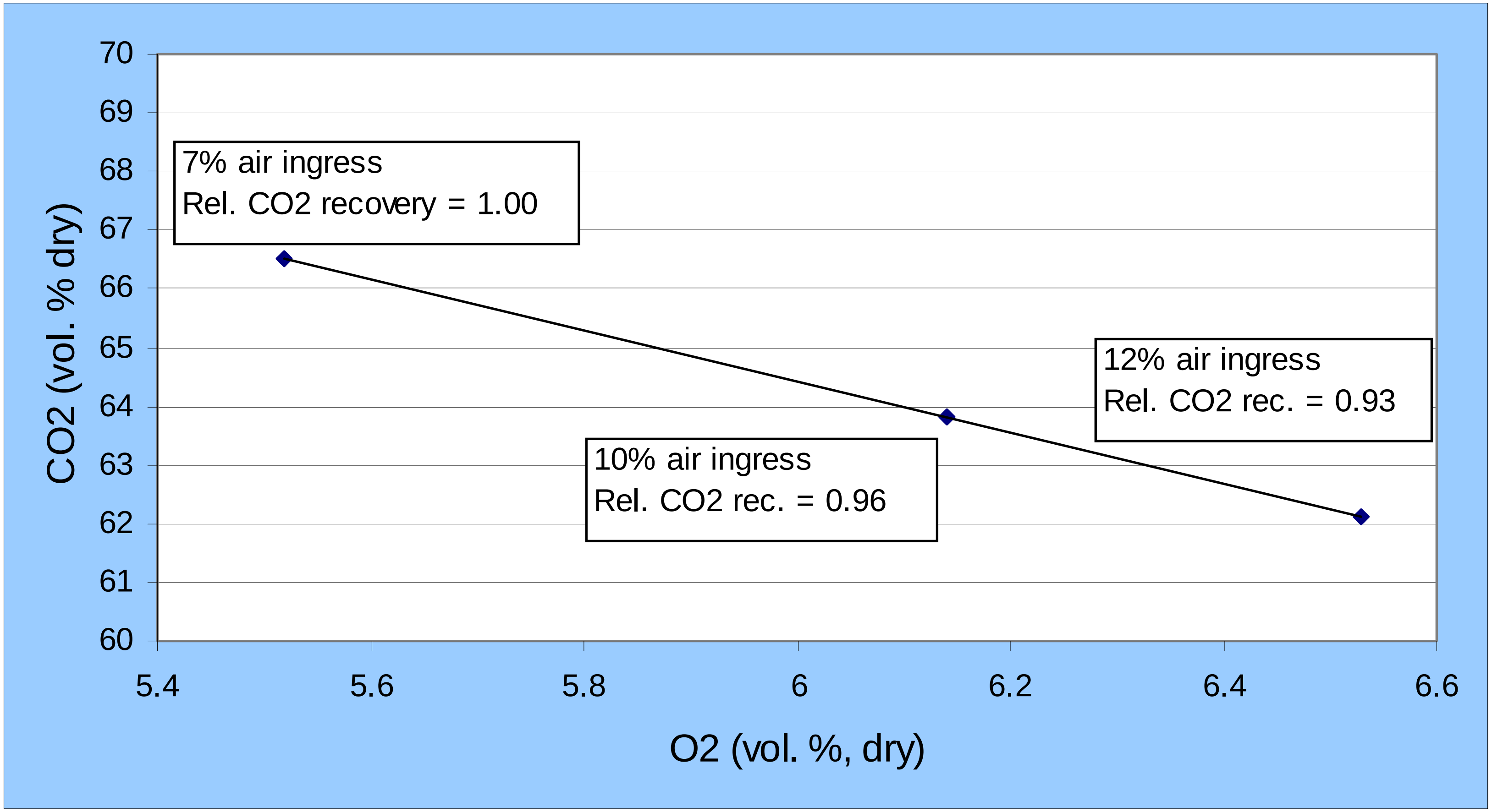
Effect of air ingress on CO2 concentration and recovery



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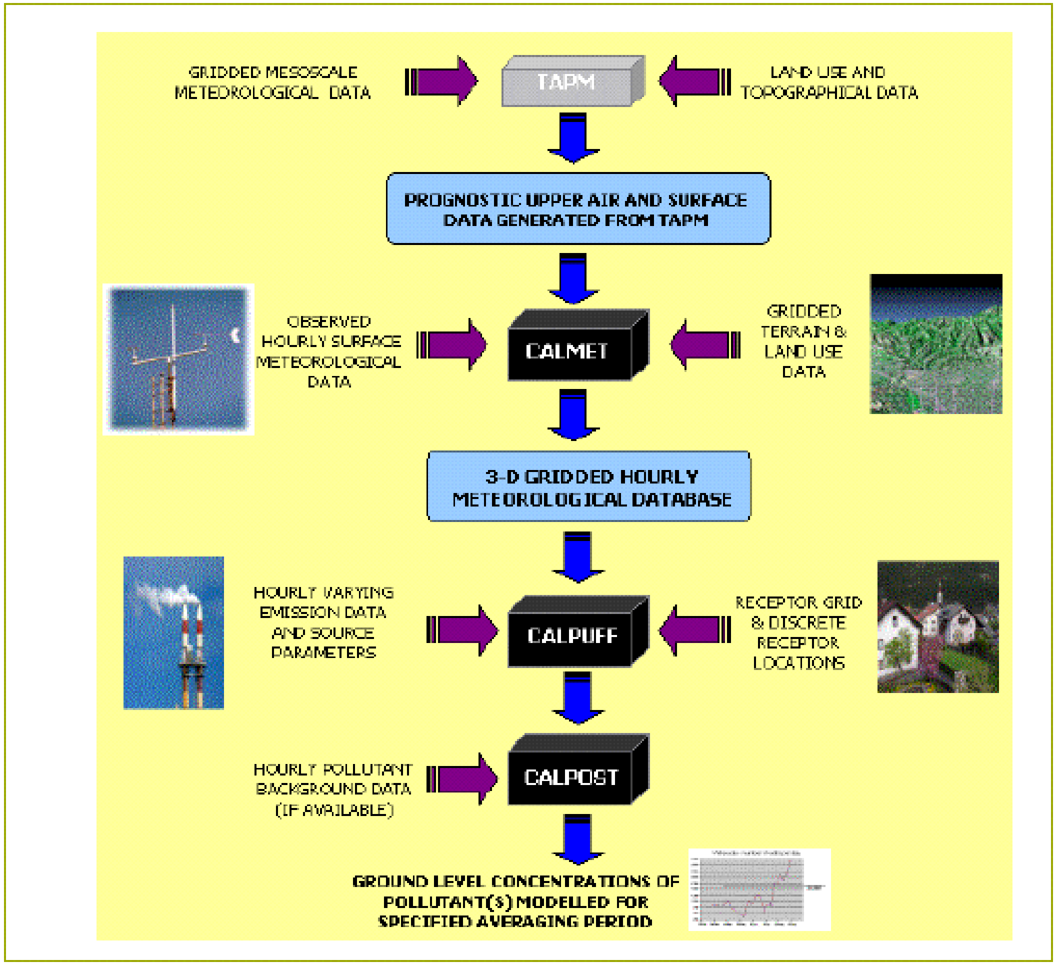
Stack emission modeling



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Stack mass emission rate data

Load Factor	%	100		70	
Fuel	GJ/s	0.105		0.076	
Firing mode		AF	OF	AF	OF
Gas to Stack	Nm3/s	39.1	10.3	28.1	5.7
NOx	g/s	44.2	15.6	31.7	13.0
SOx	g/s	22.4	15.8	16.1	13.2
Gas temperature	^{o}C	143	143	138	138
Efflux velocity	m/s	10.0	2.8	7.2	1.6

AF = Air-firing

OF = Oxy-firing

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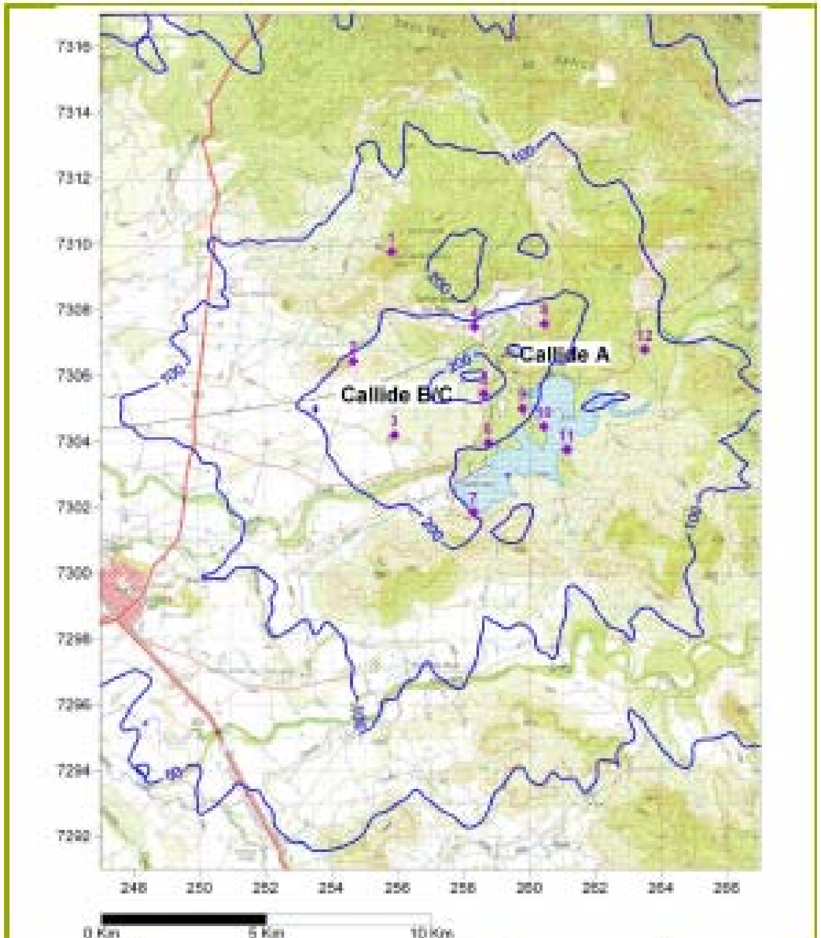
SO2 ground level concentrations (Scenario 1)



Species: SO_2	Location: Callide Power Station	Scenario: Scenario 1	Percentile: 99.9th	Averaging Time: 10-min
Model Used: CALPUFF V6	Units: µg/m³	Guideline: 700 µg/m³	Met data: January 2004 – December 2004	Plot: E Castillo

10-min conc. SO2

Callide A: 100% LF, Air-firing

Callide B: 100% LF, Air-firing

Callide C: 110% LF, Air-firing

Worst coal

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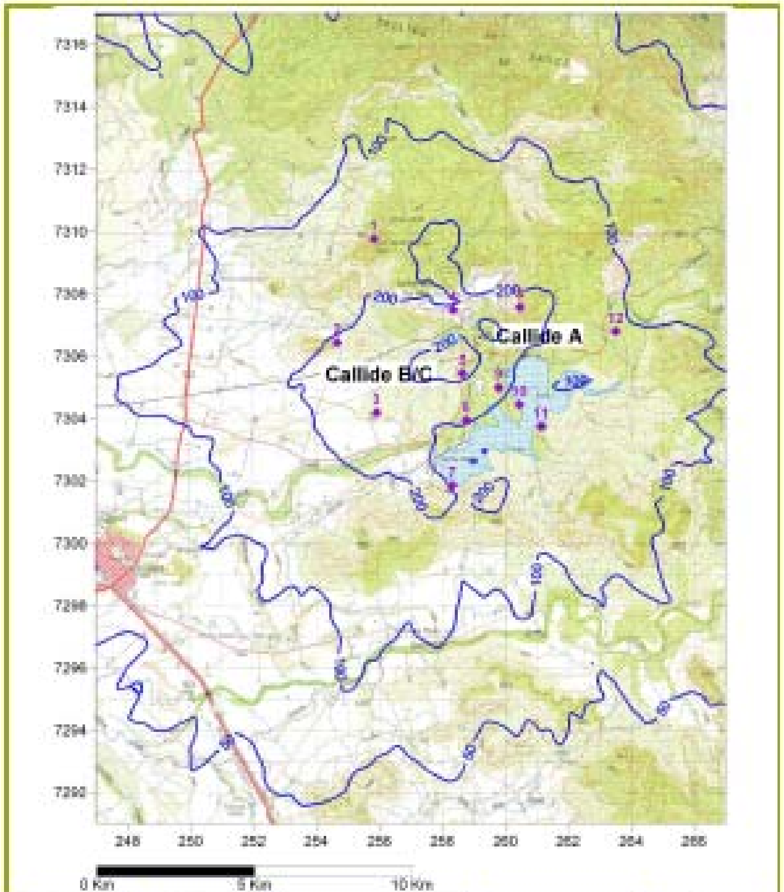
SO2 ground level concentrations (Scenario 2)



Species: SO₂	**Location:** Callide Power Station	**Scenario:** Scenario 2	**Percentile:** 99.9*	**Averaging Time:** 10-min
Model Used: CALPUFF V6	**Units:** µg/m³	**Guideline:** 700 µg/m³	**Met data:** January 2004 – December 2004	**Plot:** E Castillo

10-min conc. SO2

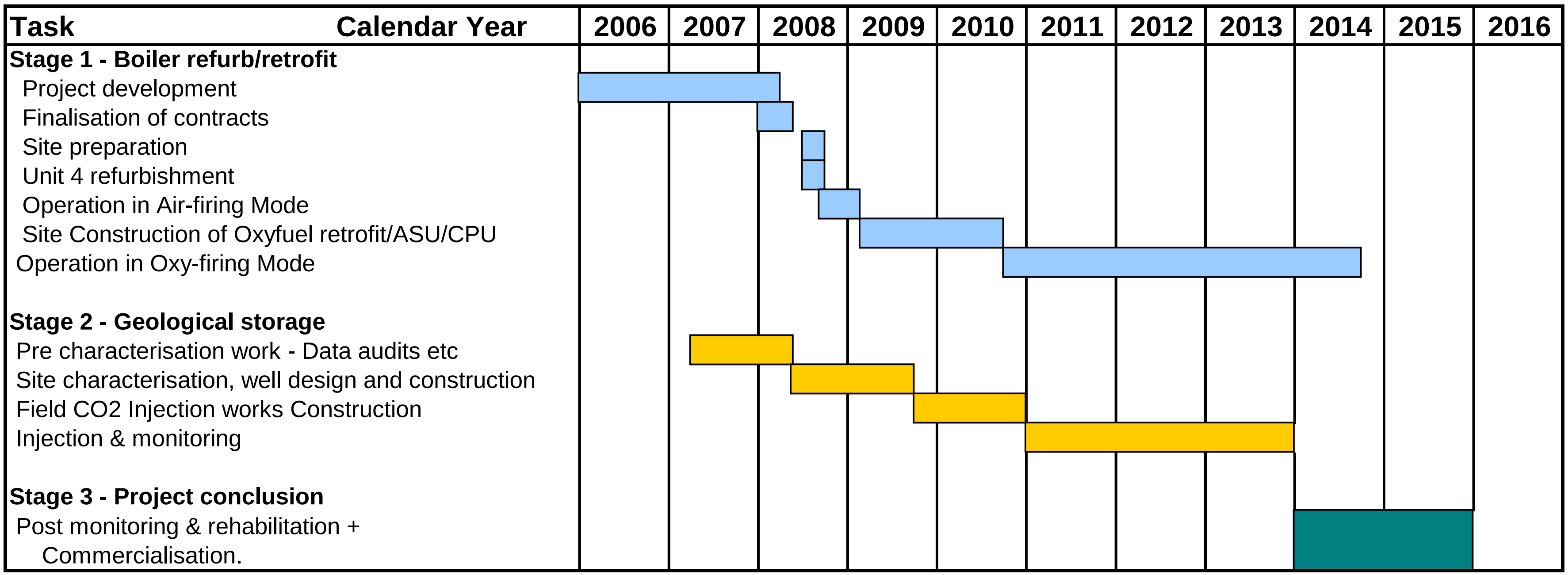
Callide A: 100% LF, Oxy-firing

Callide B: 100% LF, Air-firing

Callide C: 110% LF, Air-firing

Worst coal

Project schedule



Concluding comments

1. The Callide Oxyfuel Project is now entering the pre-construction phase with funding approved, and project agreements, and plant supply contracts at the final negotiation stage.
2. The following key activities are running in parallel to the Callide oxyfuel retrofit work program:
   - Geosequestration site selection & development (for 50,000 t CO_2 over 3 - 4 years)
   - Development of an International collaboration and supporting R&D program
   - Long-term implementation plan especially involving proving up of large CO_2 storage reservoirs and defining associated infrastructure requirements

cs energy

generations ahead

Callide Oxyfuel Project

cs energy

generations ahead

The CO_2 Pilot at Lacq

An Integrated Oxy-Combustion CO_2 Capture and Geologial Storage Project

Nicolas AIMARD, Claude PREBENDE ***Total***
Denis CIEUTAT, Ivan SANCHEZ MOLINERO, Remi TSIAVA ***Air Liquide***

3rd Workshop
IEAGHG International Oxy-Fuel Combustion Network

AIR LIQUIDE

IEA GREENHOUSE GAS R&D PROGRAMME

TOTAL

Yokohama, 5th and 6th March 2008

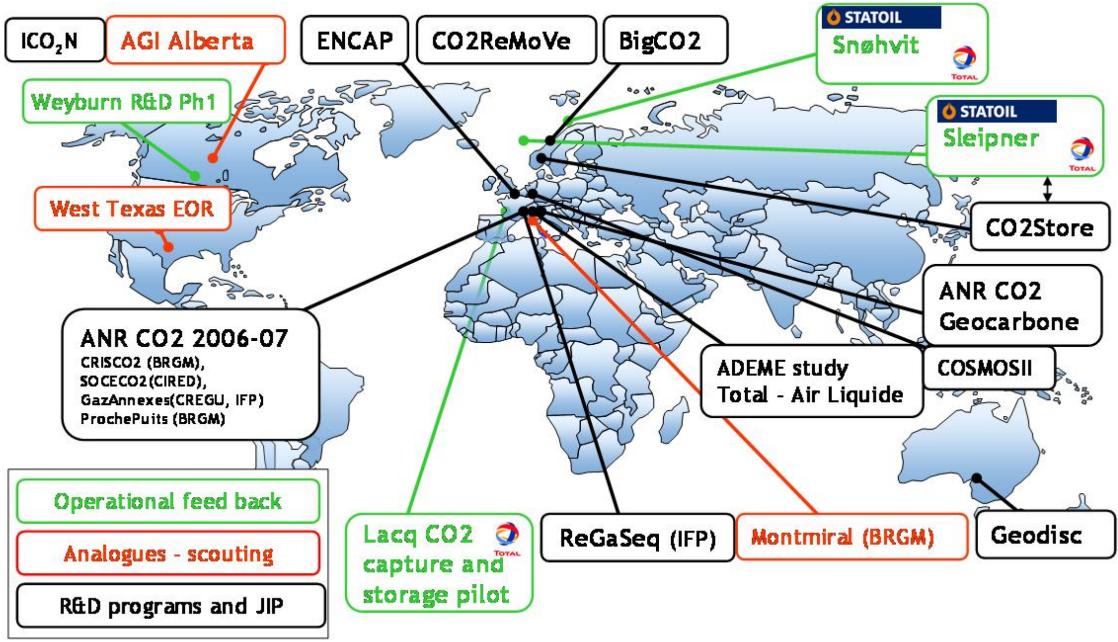
Why Total involved in Carbon Capture and Storage ?

Another option to reduce our industrial CO2 emissions :

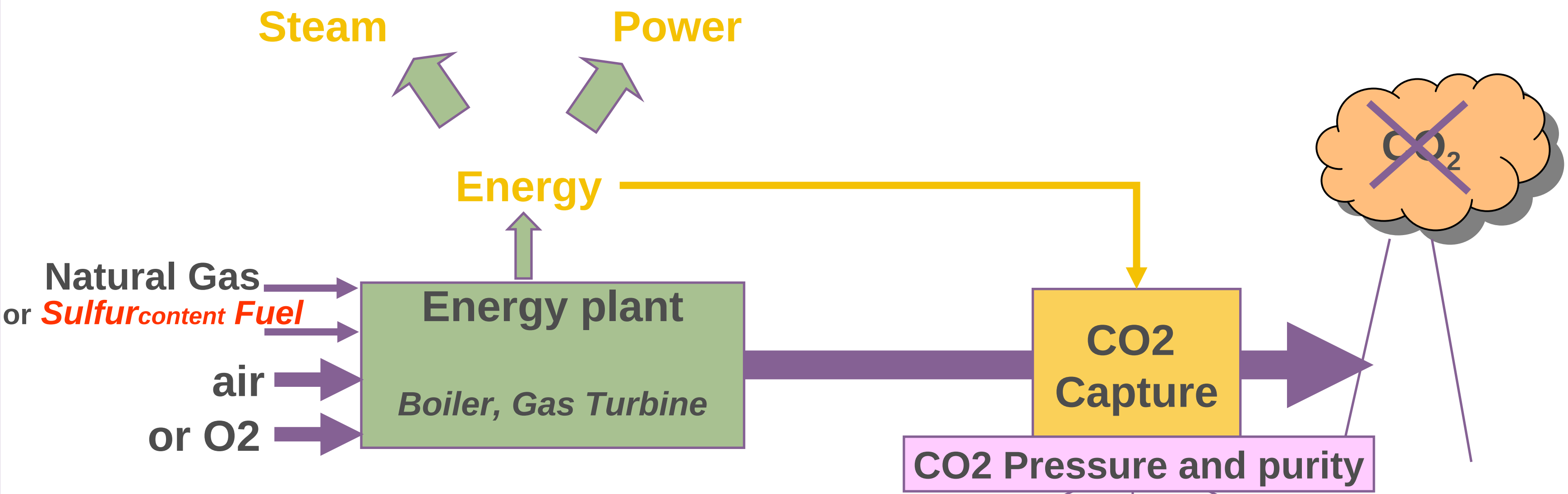
- Gas flaring reduction (world bank GGFR) on existing facilities
- Improve power efficiency
- CCS as breakthrough technology

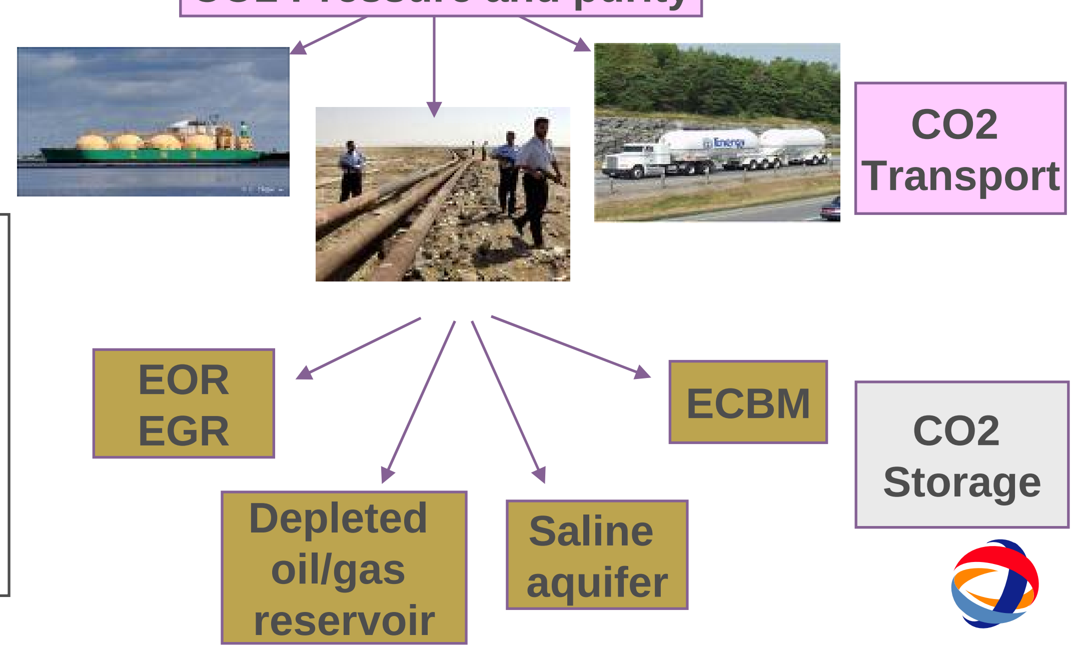
Dedicated CCS program since 2001 :

- Capture technology development
- CO_2 injection and storage
  - → Storage integrity
  - → Well integrity
  - → Long term fate of CO_2
  - → P&R, monitoring



"Capture ready" plant…. or CCS ready plant

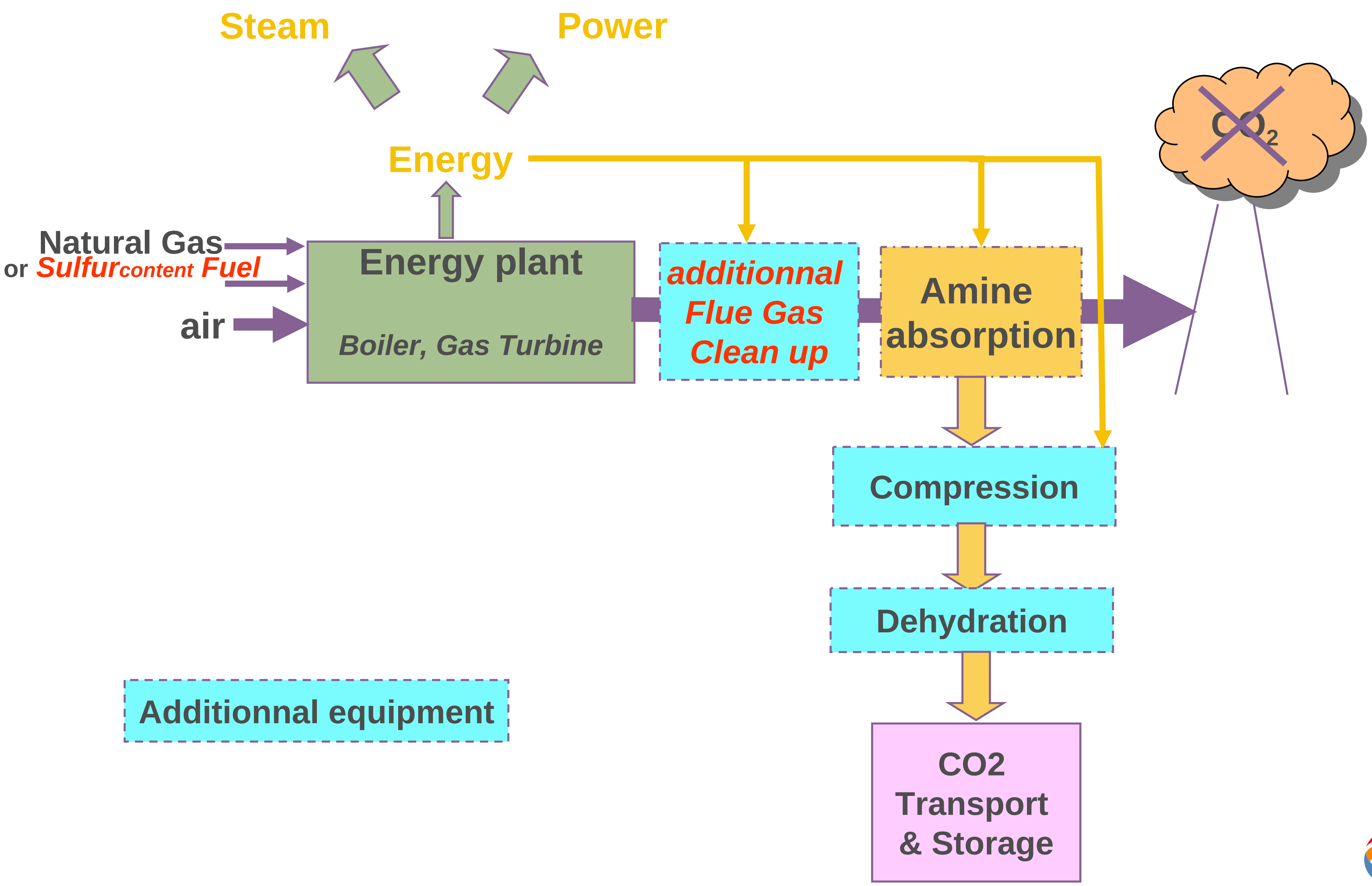




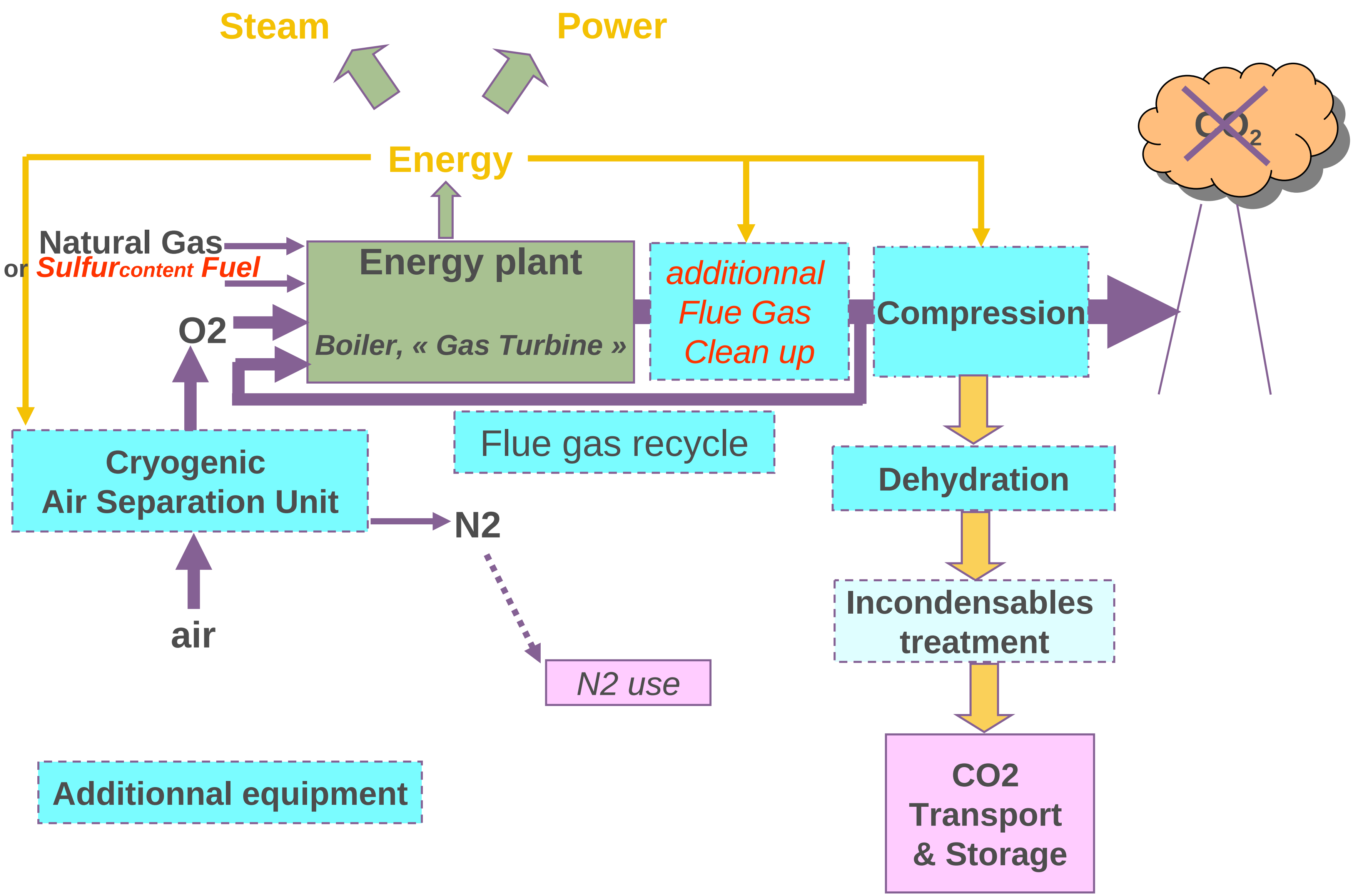
"A CO2 capture ready power plant is a plant that will be able to include CO2 capture when the necessary regulatory and/or economic drivers are in place, thereby avoiding the risk of 'stranded'assets and consequent 'carbon lock-in'"

Why Oxycombustion capture?

Post Combustion

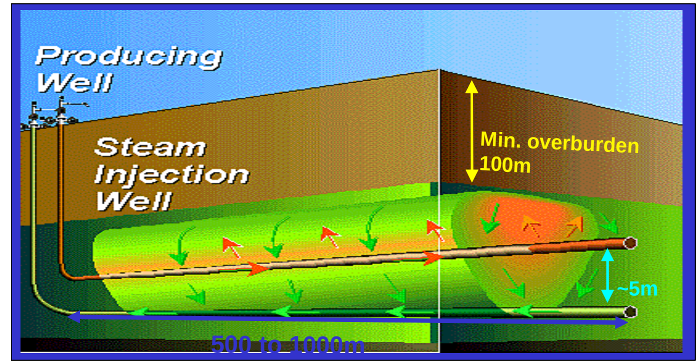


Oxy Combustion



Oil sands production

Production of Extra Heavy Oil in Athabasca (Alberta, Canada)
Use of huge quantity of STEAM
→ SAGD (Steam Assisted Gravity Drainage)



For production of 100000 bbl/d bitumen and Steam/Oil=2,5
→HP steam 39600t/d 100 bars and 312°C (1044MWth)

Steam generation by combustion of natural gas or an alternative fuel like petcoke

FUEL	BOILER	CAPTURE						
NATURAL GAS	GAS BOILER	No	Post-combustion			Oxy-combustion		
			AMINES Unit 90 % capture			Cryogenic ASU		
PETCOKE	CFB		LP Steam (t/tCO2)			O2 purity (%mol)		
			3	**2**	1.5	95	**98**	99.5

Base case

TOTAL

Oxycombustion vs Postcombustion

STEAM PRODUCTION

Efficiency and consumptions for base case – Gas or Petcoke

Perimeter :

Imported power

Auto consumed steam

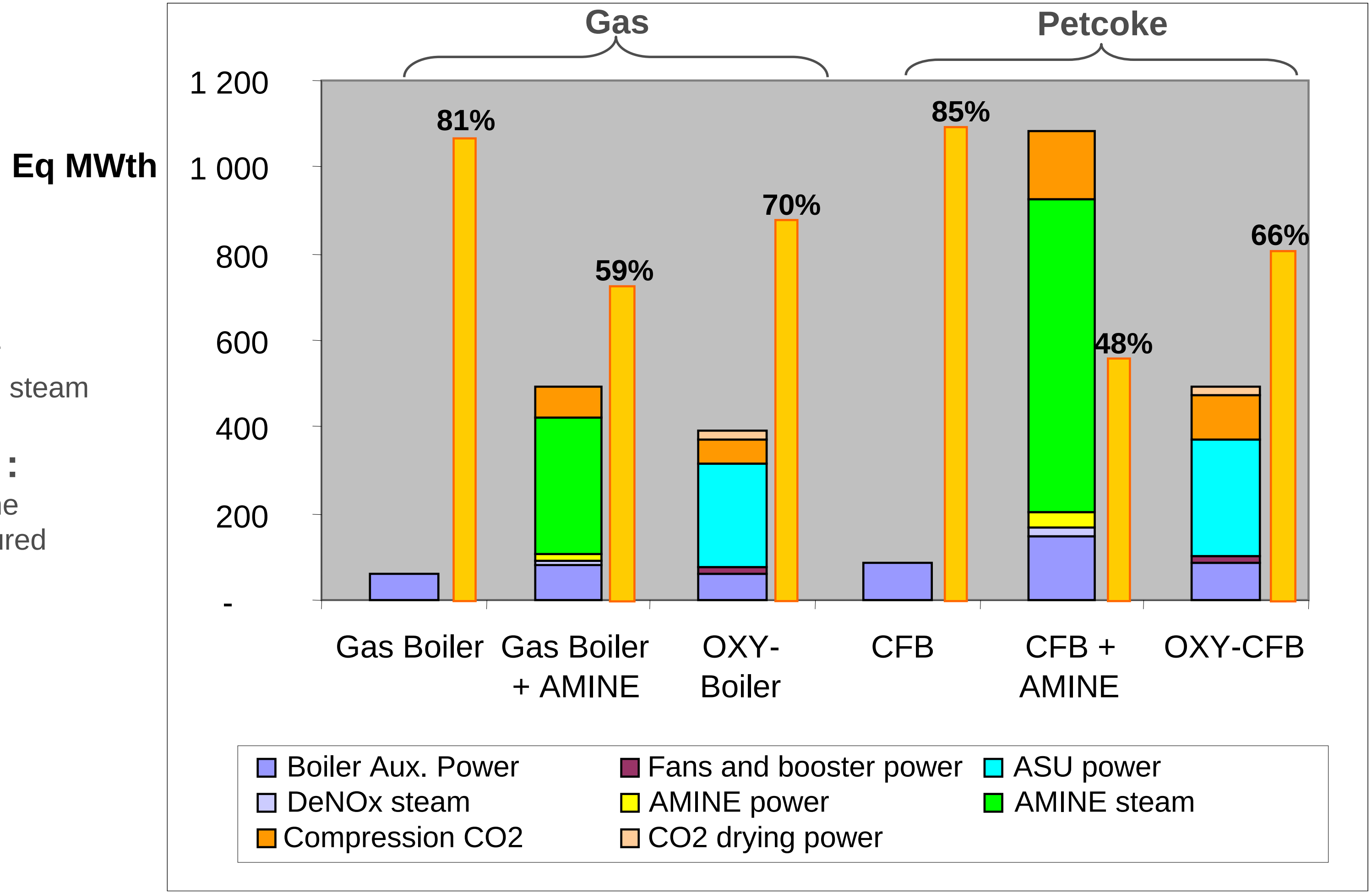
Base Case :

Fluor Econamine

90% CO2 captured

2 t steam/tCO2

ASU 98% O2

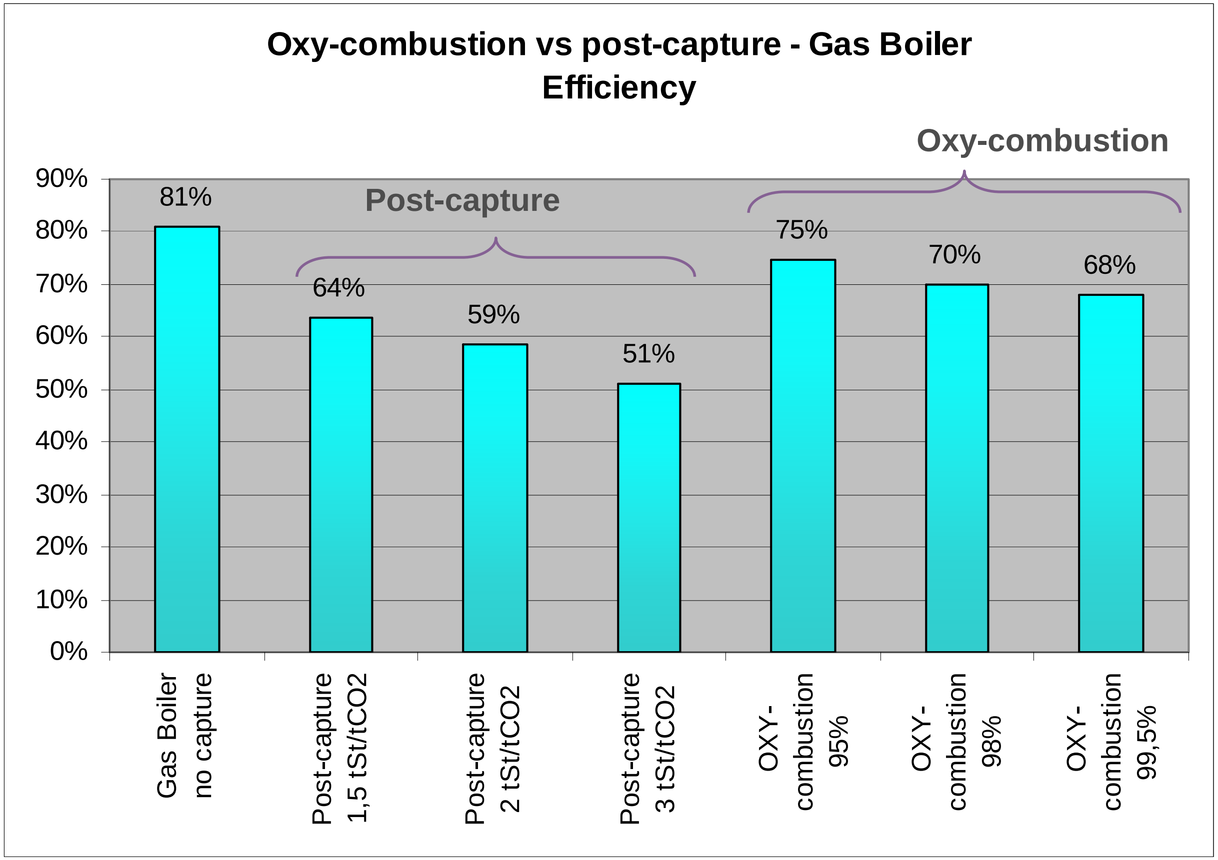


Efficiency

$$EFF = \frac{[\text{Produced - Consumed Steam}](\text{MWth})}{Q_{fuel} \times \text{LHV (MWth)} + \text{Imported power(eqMWth)}} \times 100$$

Oxycombustion vs Postcombustion

STEAM PRODUCTION
Sensivity of Efficiency



Fluor Econamine Planned target?	Fluor Econamine	MEA	95% O2	98% O2	99,5% O2

TOTAL

Oxyburners development

Oxyburner concept for Oil & Gas applications

- **Challenges for oxyburner concept:**
  - In-furnace heat flux management
  - Minimize flue gas recycle (FGR)
  - High viscosity / high density liquid fuels
  - High sulfur and high metals content
  - Use of usual materials

Oil Sands °API 5

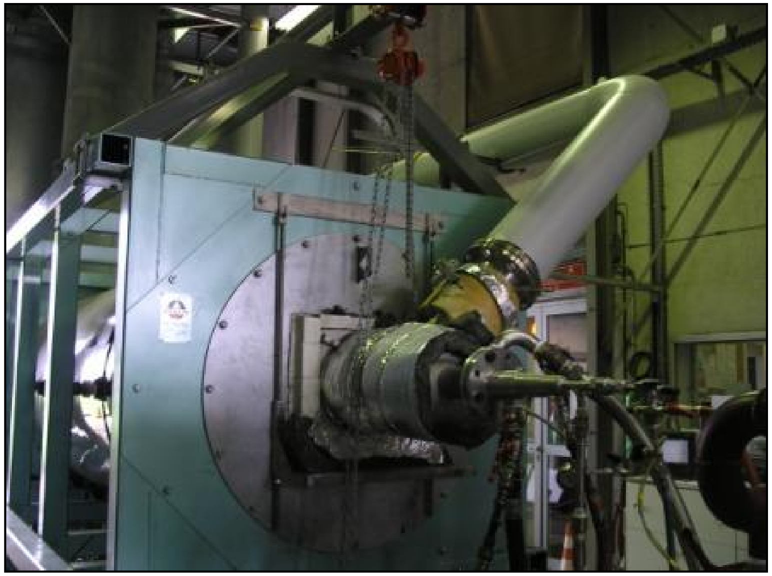
Bitumen °API 11

- **Air Liquide's oxyburner concept achieves:**
  - Fuel flexibility for gas & liquid fuels
  - Variable flue gas recycle rate
  - Air mode for transient operation
  - Important turndown ratio
  - Oxyflame stability with difficult fuels
  - Optimum operating procedures (air-oxy mode)

1 MWth Oxycombustion test rig

- **Objectives:**
  - Expand scientific knowledge on oxy-flames.
  - Contribute to industrial oxyburner design.

- **Versatile and functional test rig**
  - Variable FGR rate and temperature
  - Liquid / gas fuel feed capability
  - Cold wall configuration
  - Combustion monitoring
  - Emission control



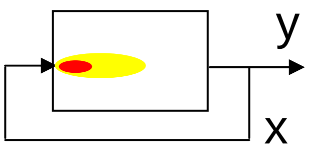
Experimental results at test rig

- **Views of 1MW oxyburner prototype with natural gas**

FGR = 0

FGR = 1

FGR = 1,5

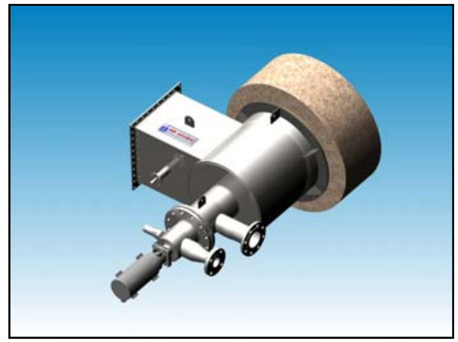


FGR rate = x / y

Oxyburner Upscaling

Size

1 MW prototype
AL-CRCD rig

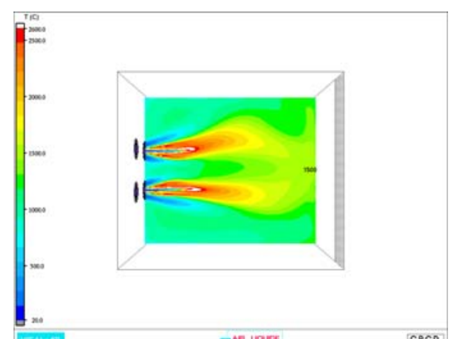


4 x 8 MW demo
Total-Lacq pilot plant

n x 30 MW
first of a kind
industrial
oxy-boiler

2006 | 2008 | > 2010

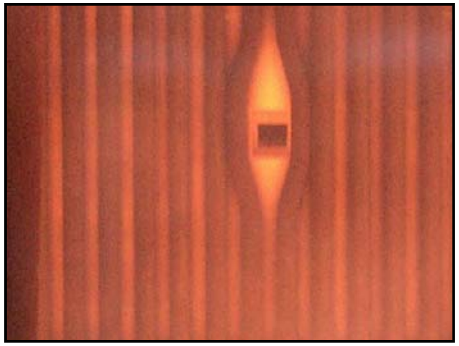
- **Upscaling know-how**
- **CFD modeling using proprietary code**
  - Specific to oxycombustion
  - Calibrated with real oxycombustion data



Oxyburner implementation into Lacq boiler

- **Retrofitting of an air-fired boiler**
  - Oil & Gas boiler configuration
  - Fixed geometry:
    - four horizontal burners
    - Chamber: L 5 m; W 4,5m; H 6-7m
- **Careful sealing at every interface to minimize air in-leakage**
- **Fluid distribution control and measurement**
- **Operating mode**
- **Safe operation Safety analysis**
- **Tests and measurement plans**

Openings for the four existing air-fired natural gas burners



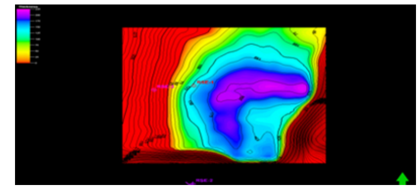
Existing measurement port

Oxycombustion and CO2 storage pilot

TOTAL

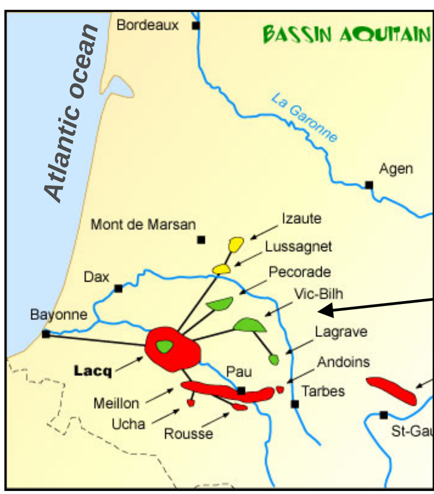
General objectives of the Lacq pilot

CO_2 Capture → **CO_2 transport and injection** → **CO_2 storage**



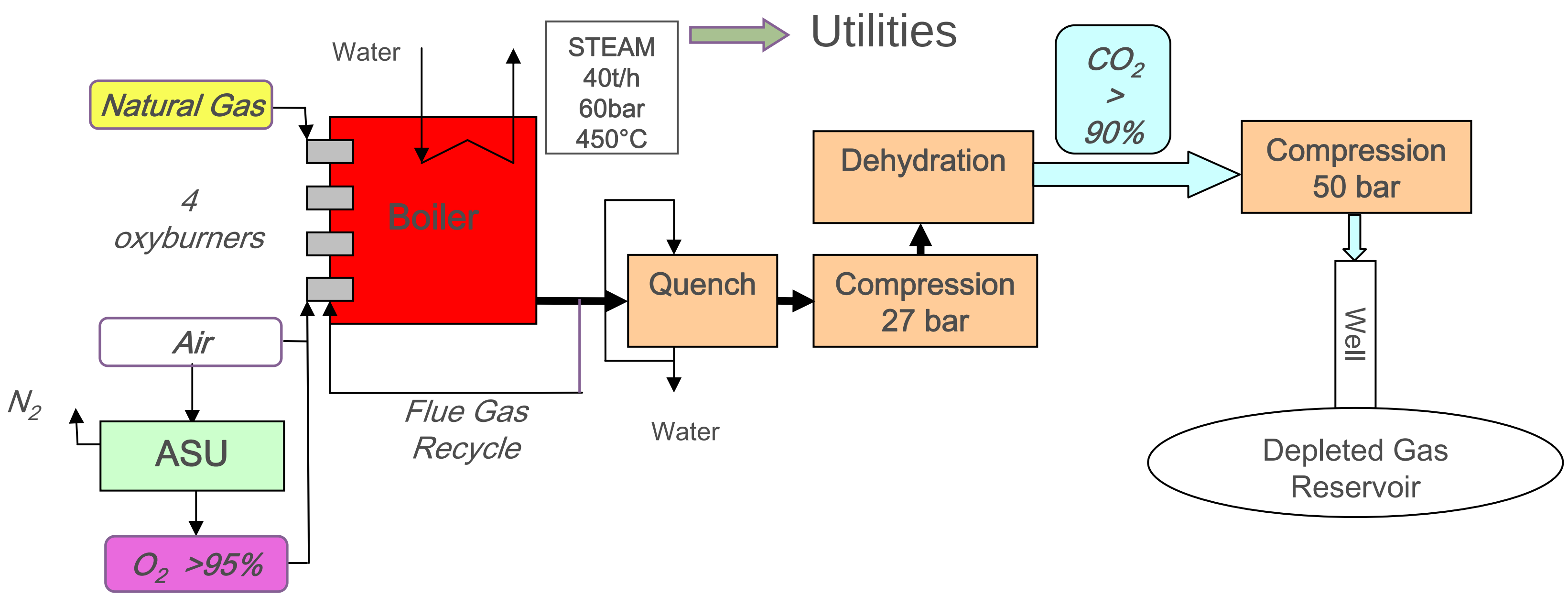
- Contribute to a potential climate change mitigation technology
- Demonstrate the technical feasibility and reliability of **an integrated CO_2 capture, transportation, injection and storage** scheme for steam production at a reduced scale (1/10th of future facilities)
- Design and operate a 30MWth oxycombustion boiler for CO_2 capture
- Develop and apply geological storage qualification methodologies, monitoring and verification techniques on a real operationnal case to prepare future larger scale long term storage projects

Pilot location
Total Exploration & Production in France



Gas field
Oil field
NG Storage

CCS Lacq pilot to start beginning 2009

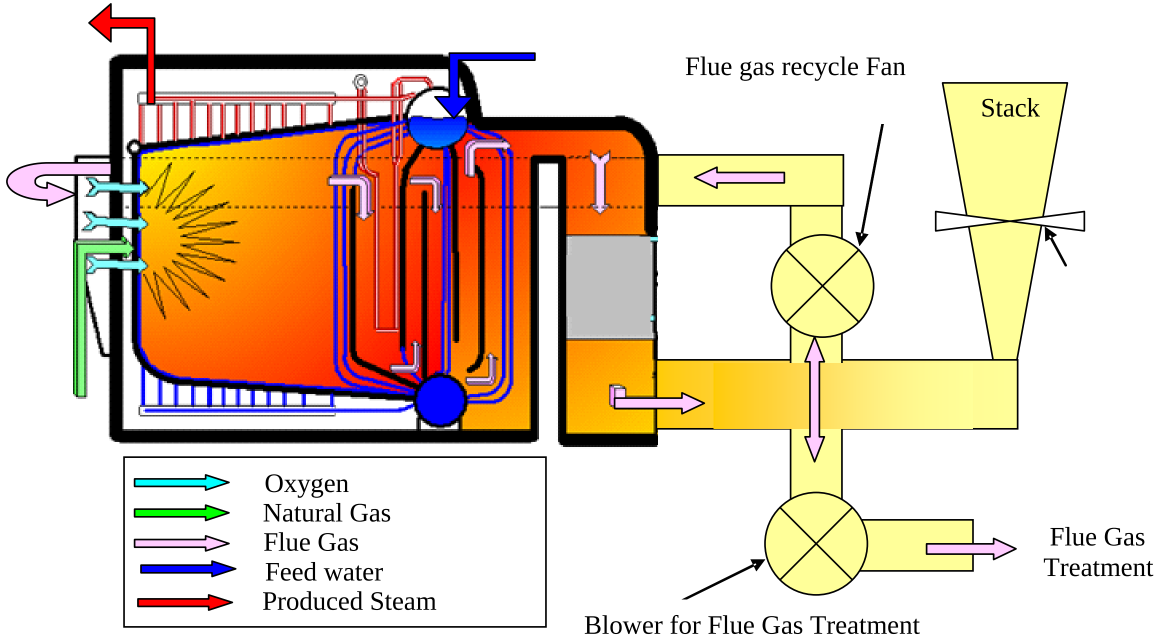


CHALLENGES

- ✓ **Industrial scale 30MWth oxycombustion unit with gas**
- ✓ **Revamping of a conventional boiler**
- ✓ **CO2 transport and injection for 2 years**
- ✓ **150 kt CO2 storage in a depleted reservoir**
- ✓ **First CO2 injection for storage in France**
- ✓ **Public acceptance with consultation and dialogue**
- ✓ **French and international legal framework not frozen**

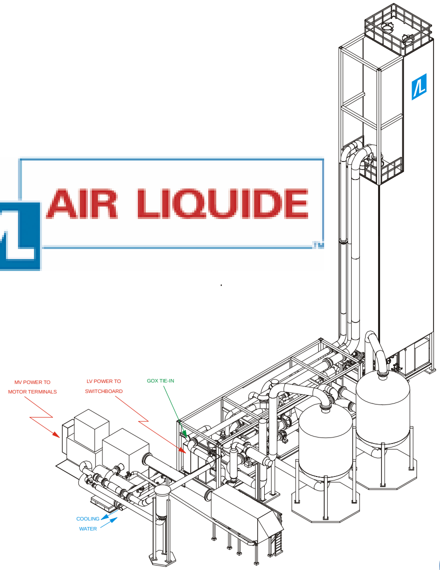
Boiler and ASU

- ➢ Existing boiler revamping with CO2 recycling
- ➢ 40 t/h of steam 60b/450°C (30MWth) to HP steam network



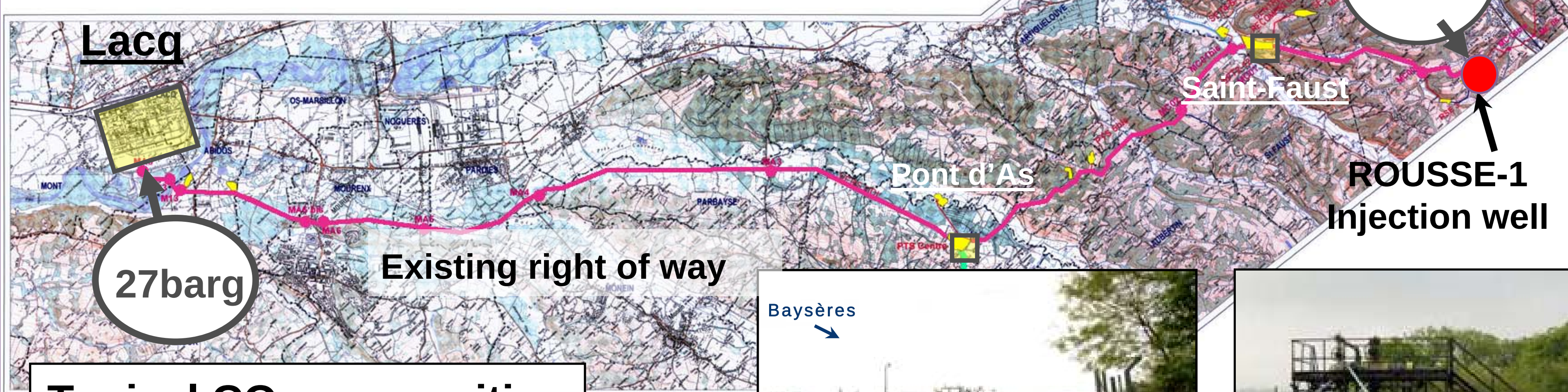
- ➢ ALSTOM in charge of boiler revamping works
- ➢ Cryogenic Air Separation Unit
  - Standard ASU packaged plant
  - 240 tpd O_2
  - LP: 1,8 bar abs
  - Variable purity (95-99,5% O_2)
  - No oxygen storage

AIR LIQUIDE



TOTAL

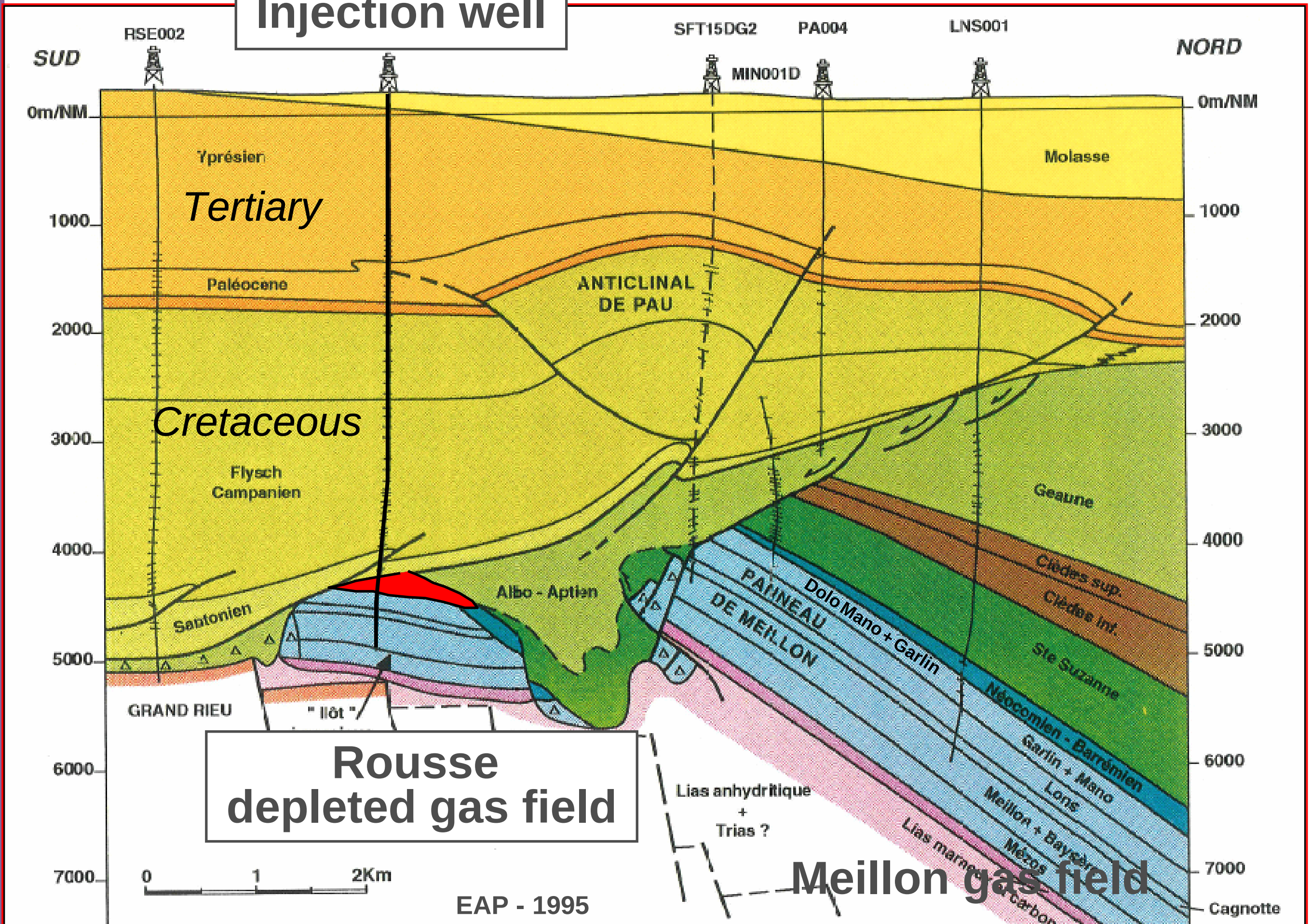
Transportation and injection into a gas depleted reservoir



Typical CO_2 composition

CO_2	92.0 %
O_2	4.0%
Ar	3.7%
N_2	0.3%

CO_2 injection into a depleted gas reservoir



Jurassic fractured dolomitic reservoir *(in red)*

Thick cap rock *(in green and orange)*

Depth # 4500m/MSL

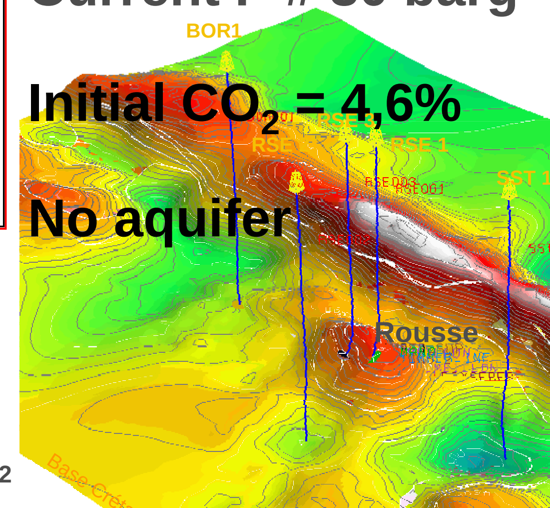
Temp. # 150°C

Initial P = 485 barg

Current P # 30 barg

Initial CO_2 = 4,6%

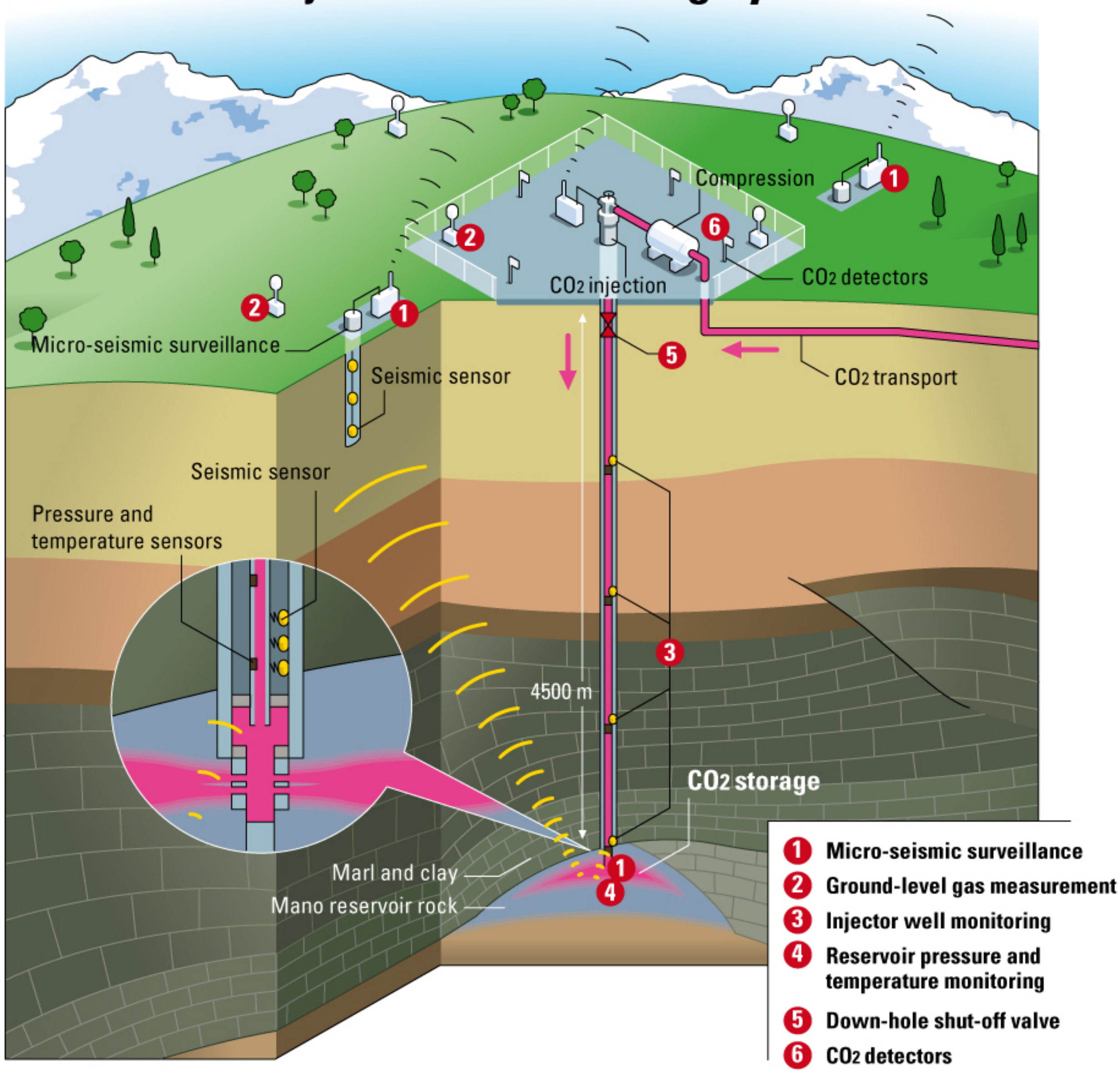
No aquifer



Existing unique well RSE-1 producing since 1972

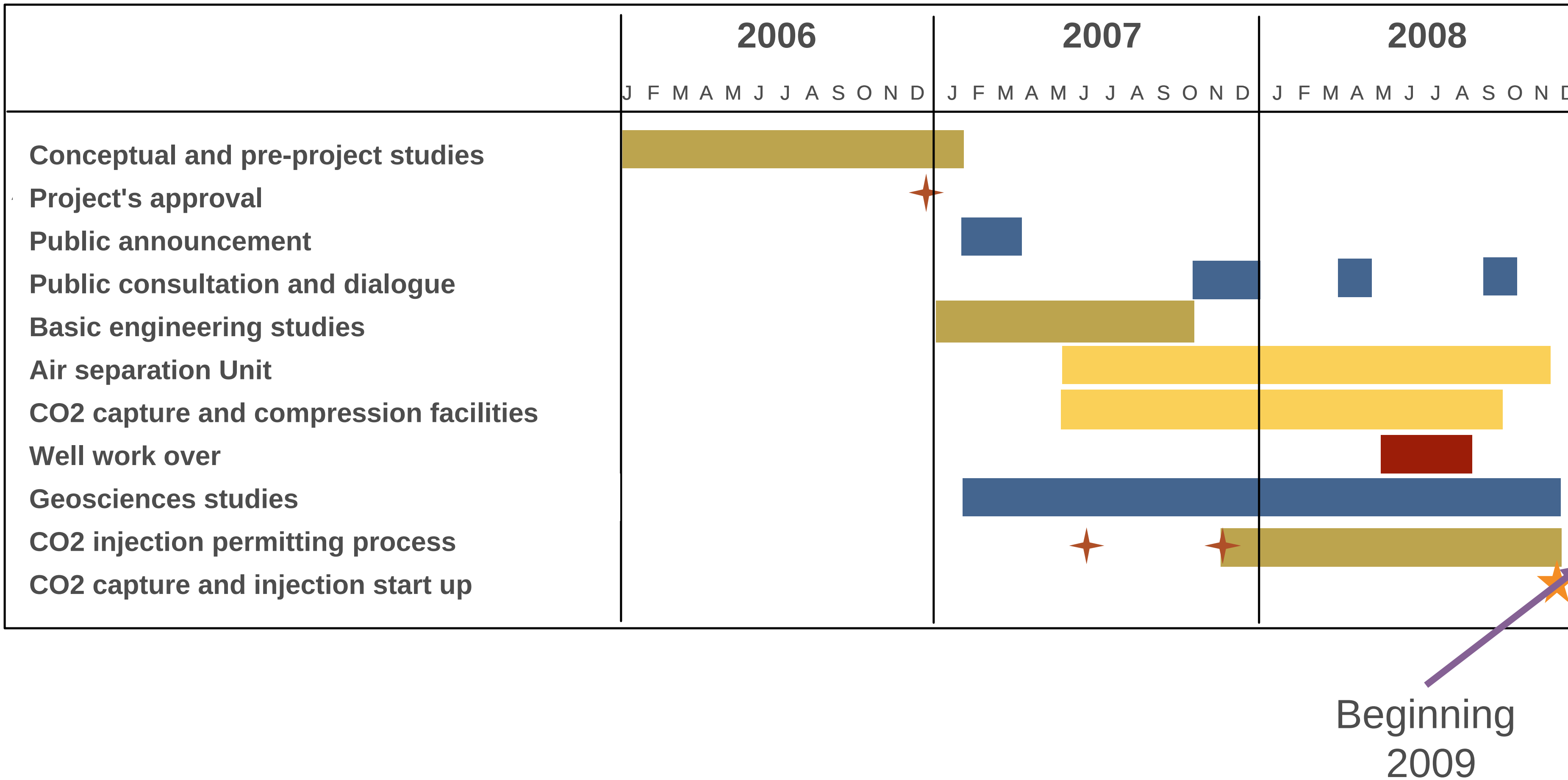
Well work over planned mid 2008

Lacq CO_2 pilot
CO_2 injection - monitoring system



TOTAL

Project schedule – main milestones



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Thank you for your attention

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ciudad de la energía

Gobierno de España

TEST FACILITY FOR ADVANCED TECHNOLOGIES FOR CO_2 CAPTURE IN COAL POWER GENERATION

UPDATE AND UPGRADE

Prof. Dr. Vicente J. Cortés

CO_2 Capture Program Director

CIUDEN, SPAIN

I. Fundación Ciudad de la Energía

II. Conceptual design. Size and technologies

III. The site. Design criteria and plant configuration

IV. Virtual walkthrough

V. Project structure

VI. Research Program

VII. Time schedule

ciudad de la energía

Gobierno de España

TEST FACILITY FOR CO_2 CAPTURE TECHNOLOGIES EL BIERZO

Fundación Ciudad de la Energía
A brief introduction

Prof. Dr. V. J. Cortés

An initiative of the Spanish Administration

MINISTERIO DE EDUCACIÓN Y CIENCIA

MINISTERIO DE INDUSTRIA

Gobierno de España

MINISTERIO DE MEDIO AMBIENTE

Objectives and activities

Promote and financially support R&D+d for CO_2 capture and storage technologies and abandoned mines restoration

PROGRAM A

TEST FACILITY
FOR CO_2
CAPTURE TECHNOLOGIES

ADDRESSING

OXYFUEL
AND POST-COMBUSTION
TECHNOLOGIES
AT
EL BIERZO

PROGRAM B

CO_2 GEOLOGICAL
STORAGE

ADDRESSING

FULL SIZE INJECTION TESTS
IN SUITABLE GEOLOGICAL
FORMATIONS IN SPAIN

PROGRAM C

ABANDONED LAND
ACTION PLAN

ADDRESSING

RESTORATION OF
LAND RESOURCES
THROUGH REVEGETATION
FOR LANDSCAPE
RECOVERY

Conceptual design: Size and technologies

Prof. Dr. V. J. Cortés

ZEP Recommendations

ZEP
Technology Platform
Zero Emission Fossil Fuel Power Plants

Recommendations for RD&D priorities within FP7 Energy and National RTD Work Programmes 2008

Revised Version 6th Draft 15th February 2008

R&D area: Developing and implementing OXY-FUEL combustion for boilers

1. Pilot plant tests (10s of MWth) of full oxy-fuel pulverised fuel (PF) process, to validate results from scale-up based on laboratory tests.
2. Development of PF burner designs and piloting in 10s of MWth scale
3. Pilot plant tests (10s of MWth) of full oxy-fuel CFB

Comparison of main characteristics of CCS options

	Suitable/applicable					Does not require	
Technology	**Existing PF Plant**	**New PF Plant**	**CFB Plant**	**Capture-ready Plants**	**Slip-stream of flue gas**	**O_2 supply**	**CO_2 capture prior to compression**
Post	X	X	X	X	X	X	
Pre				X, But unlikely	X, But unlikely		
Oxy	X	X	X				X

X: Desirable characteristic

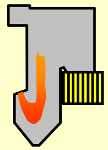
Addressed at El Bierzo

Adapted from: **Wall, T.F.: Combustion Processes for Carbon Capture. Proc. Comb. Inst., 31 (2007) 31-47**

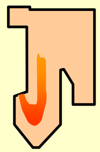
The upgrade

ORIGINAL DESIGN JANUARY 07

OXYBOILER
(4 MWth)



CONVENTIONAL BOILER
(4 MWth)



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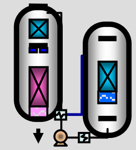
POST-COMBUSTION ABSORPTION
(O,5 MWth)



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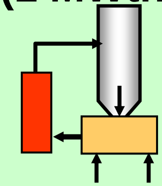
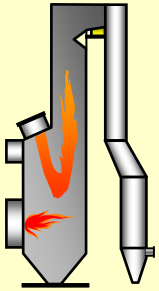
POSTCOMBUSTION ADSORPTION
(1 MWth)

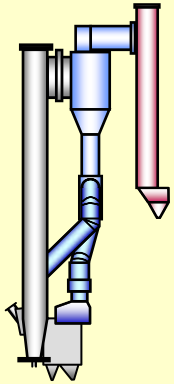


REVISED DESIGN NOVEMBER 07

OXYBOILER
(20 MWth)



LFC
(15-30 MWth)



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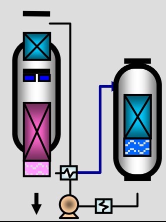
POST-COMBUSTION ABSORPTION
(4 MWth)



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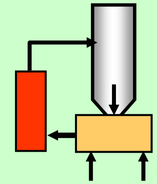
POSTCOMBUSTION ADSORPTION
(X MWth)



The site

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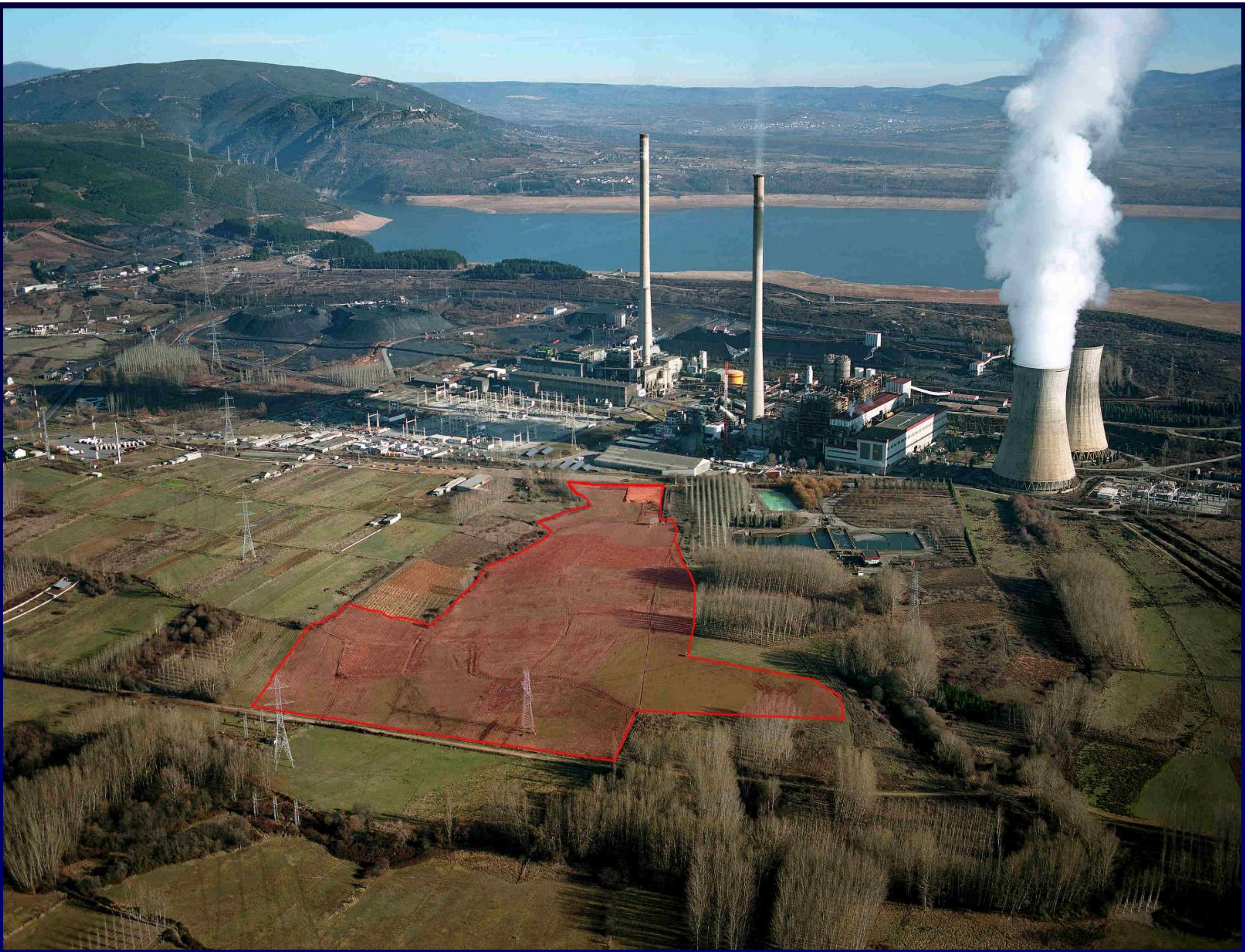
TEST FACILITY FOR CO_2 CAPTURE TECHNOLOGIES EL BIERZO



Design criteria and plant configuration

Prof. Dr. V. J. Cortés

General design criteria

MODULARITY	LAY-OUT AS INDEPENDENT BUT INTERCONNECTED MODULES (OXYCOMBUSTION, FLUE GAS TREATMENT…) ALLOWING SIMULTANEOUS OR SEPARATE OPERATION FOR INDEPENDENT STUDY OF PROCESSES
FLEXIBILITY	OPERATION UNDER A WIDE RANGE OF CONDITIONS, INCLUDING DIFFERENTS COALS AND COMBUSTION FROM AIR MODE TO OXYMODE
INTEGRATION	DESIGNED TO STUDY FULL PROCESS INTEGRATION OF THE DIFFERENT UNITS AND SYSTEMS
EFFICIENCY	CONCEIVED TO EXPLORE HEAT INTEGRATION AND PERFORMANCE OPTIMISATION WITHOUT PUTTING INTO COMPROMISE REQUIREMENTS FOR FLEXIBLE TESTING
EXTENSION	LAY-OUT ALLOWING FOR EXTENSIONS AT A LATER STAGE IN LINE WITH ANY TECHNOLOGICAL PROGRESS AND/OR STRATEGIC DEVELOPMENT

The facility

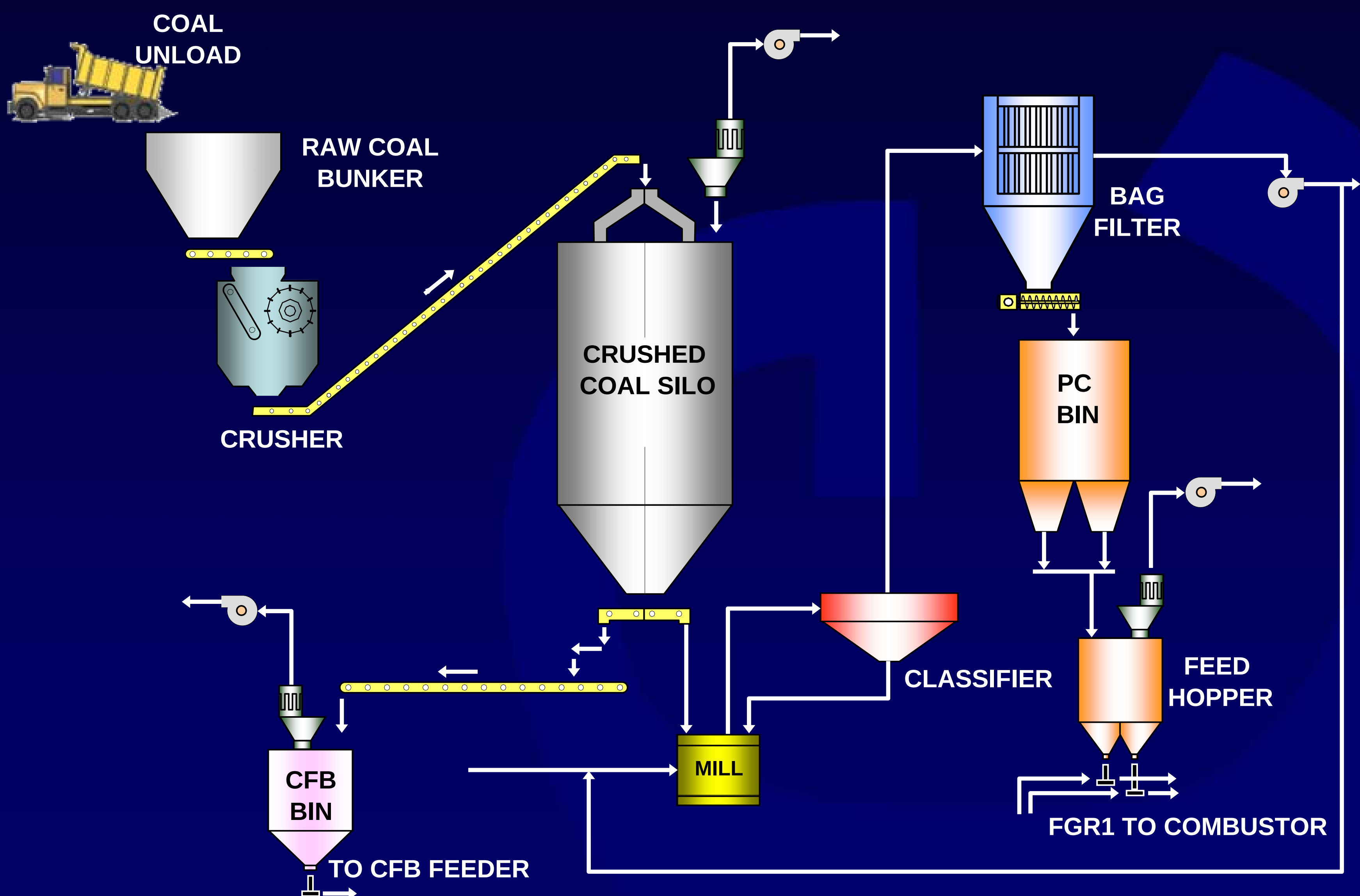
A. COMBUSTION SECTION
- ✓ FUEL PREPARATION/FEEDING WITH INTERMEDIATE STORAGE OF PULVERIZED COAL
- ✓ LIMESTONE PREPARATION/FEEDING
- ✓ PC BOILER, 20 MWth
- ✓ CFB BOILER, 15 MWth (AIR), 30 MWth (OXYGEN)
- ✓ HEAT RECOVERY SECTION

B. FLUE GAS CLEANING SECTION
- ✓ SCR
- ✓ FF
- ✓ WET FGD

C. CO_2 CAPTURE SECTION
- ✓ COMPRESSION/COOLING UNIT FOR OXY-FLUE GASES
- ✓ CHEMICAL ABSORPTION UNIT FOR AIR-FLUE GASES (PHASE II)

D. O_2 SUPPLY SECTION
- ✓ CRYOGENIC STORAGE + VAPORIZING SYSTEM
- ✓ AIR SEPARATION UNIT (PHASE II)

Coal preparation section “Indirect” combustion



Design coals

Proximate analysis as received (wet)	Anthracite I	Bituminous Coal	Sub-Bituminous Coal	Pet Coke
Moisture (%)	8.8	7.5	26.8	6.8
Volatiles (%)	6.5	22.3	36.8	10.6
Ash (%)	32.0	13.8	1.5	0.8
Fixed carbon (%)	52.7	56.4	34.9	81.8
Ultimate analysis as received (wet)				
C (%)	52.59	66.91	52.66	79.82
H (%)	1.68	3.37	3.76	3.93
N (%)	0.88	1.65	0.66	1.78
S (%)	1.07	0.38	0.09	5.11
O (%)	2.95	6.34	14.59	1.70
High heat value				
H.H.V. (kcal/kg) as received (wet)	4888	6550	4941	7785

PC boiler (by FW) main characteristics

Height (m)	19.5	
Wide(m)	4.3	
Depth (m)	2.4	
Burners	2 vertical + 2 horizontal	
Heat transfer system	Evaporator + drum + superheater + economizer	
Design data (for Cupo Bierzo Coal)	Air mode	Oxymode
Thermal Power (MW HHV)	20	20
Air flow (kg/h)	27068	0
Oxygen flow (kg/h)	0	7880
Recirculation gas (kg/h)	0	19757
Exhaust gas (kg/h)	29213	27814
Exhaust gas temperature (°C)	350	350
Coal consumption (kg/h)	3278	3278
Steam generation (t/h)	32	32
Steam Pressure (bar) / Temperature (°C)	30 / 250	

CFB (by FW) main characteristics

Height (m)	21		
Wide(m)	2.7		
Depth (m)	2.4		
Heat transfer system	Evaporator + drum + intrex + superheater + economizer		
Design data (for Cupo Bierzo Coal)	Air mode	Oxy mode	
Thermal Power (MW HHV)	14	16	30
Air flow (kg/h)	21240	0	0
Oxygen flow (kg/h)	0	4748	8775
Recirculation gas (kg/h)	0	24327	25532
Exhaust gas (kg/h)	23040	29520	28800
Exhaust gas temperature (°C)	346	358	355
Coal consumption (kg/h)	2703	2846	5469
Limestone consumption (kg/h)	278	354	720
Steam generation (t/h)	21.6	22.7	44.6
Steam Pressure (bar) / Temperature (°C)	30 / 250		

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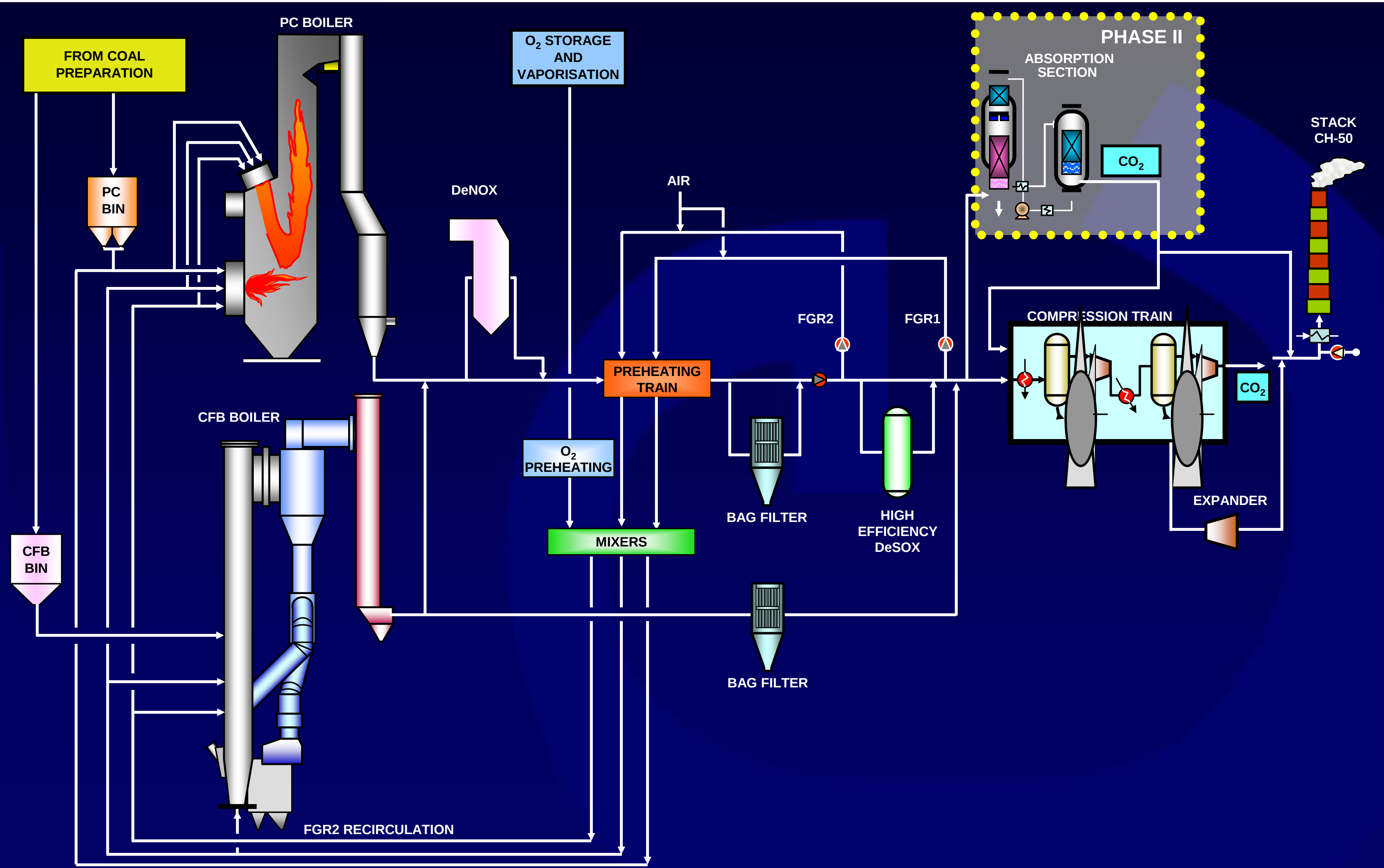
Simplified process diagram

TEST FACILITY FOR CO_2 CAPTURE TECHNOLOGIES EL BIERZO



Prof. Dr. V. J. Cortés

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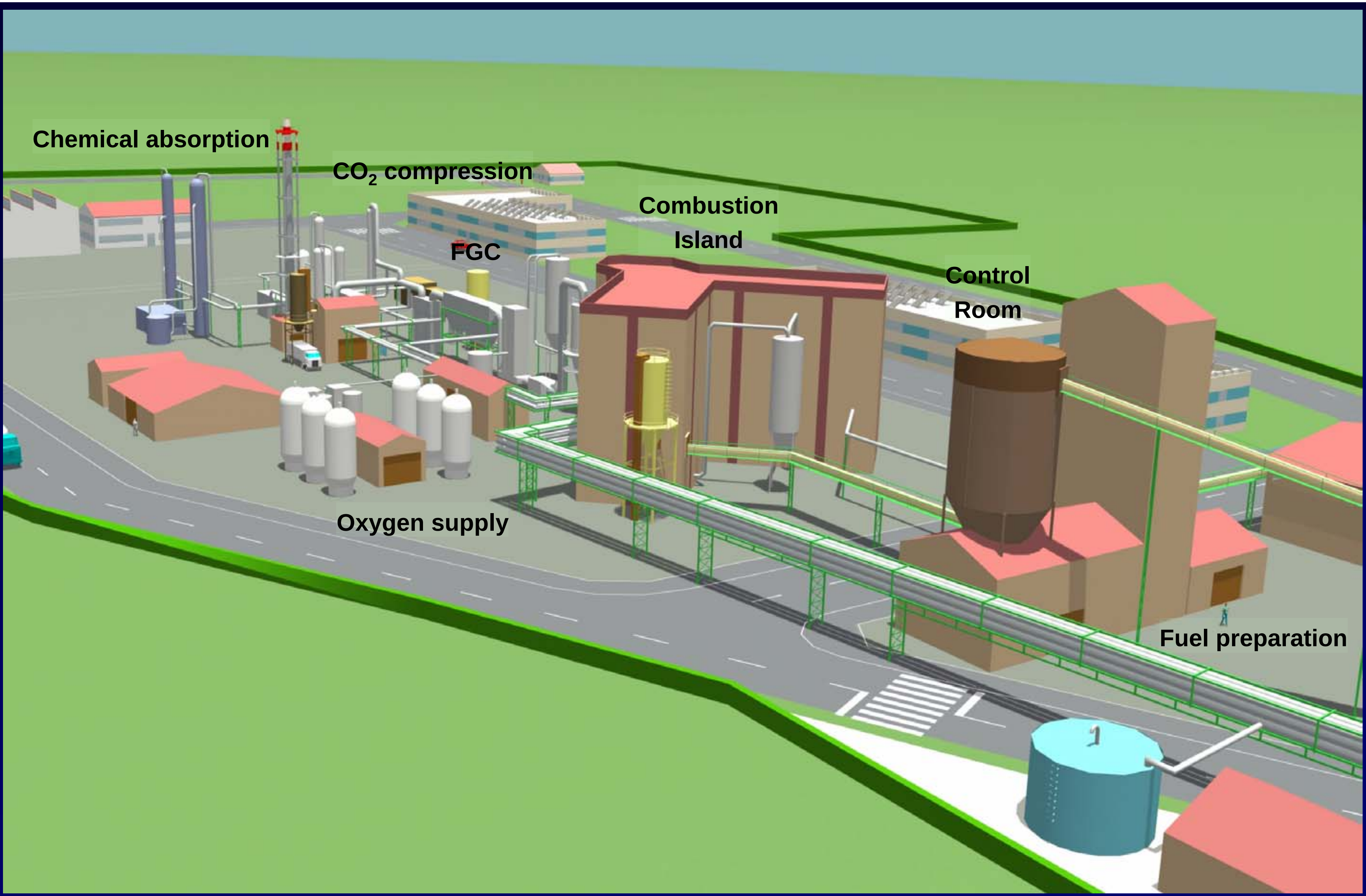
TEST FACILITY FOR CO_2 CAPTURE TECHNOLOGIES EL BIERZO

Virtual walkthrough

Prof. Dr. V. J. Cortés

Model of the plant



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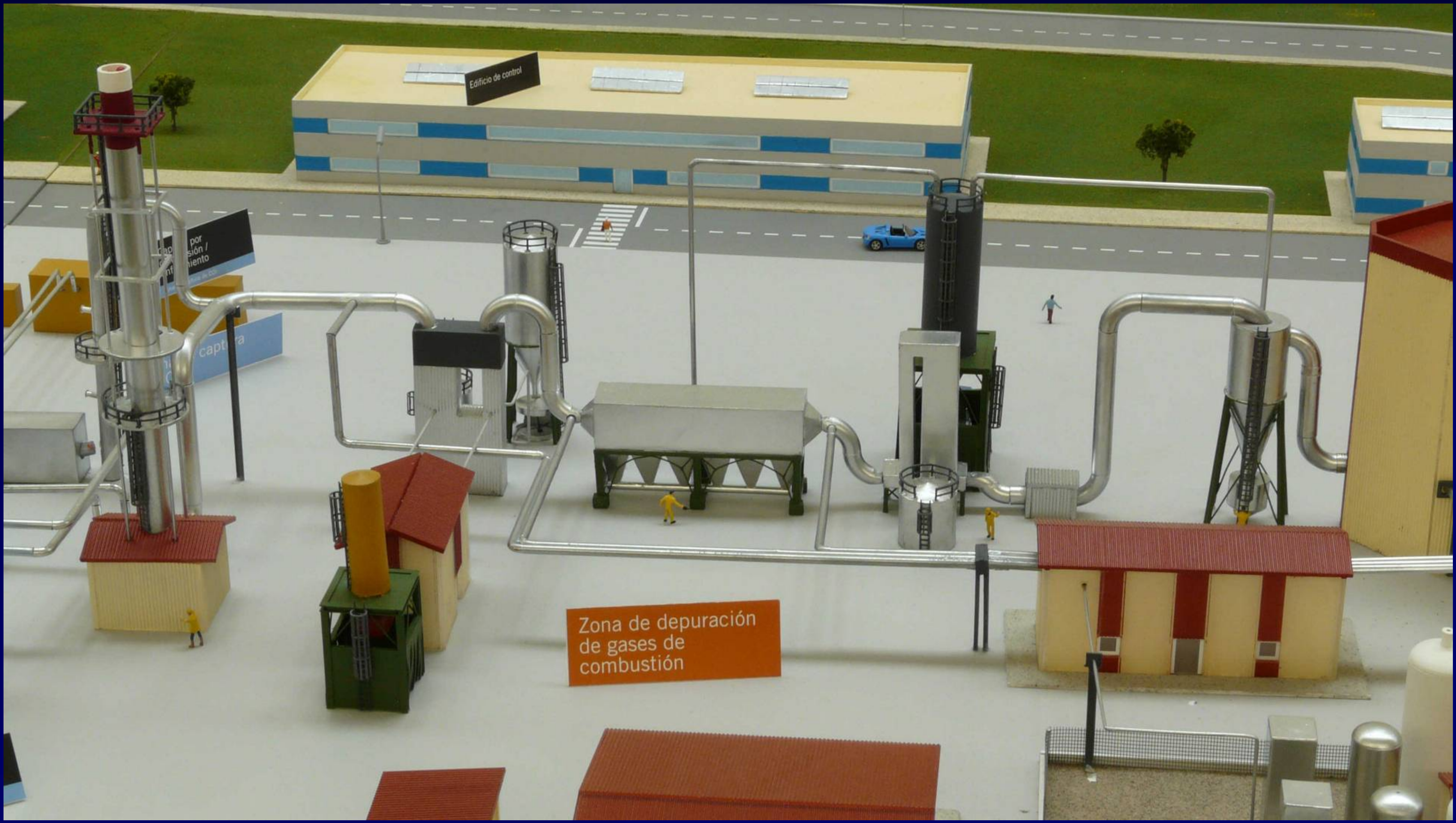
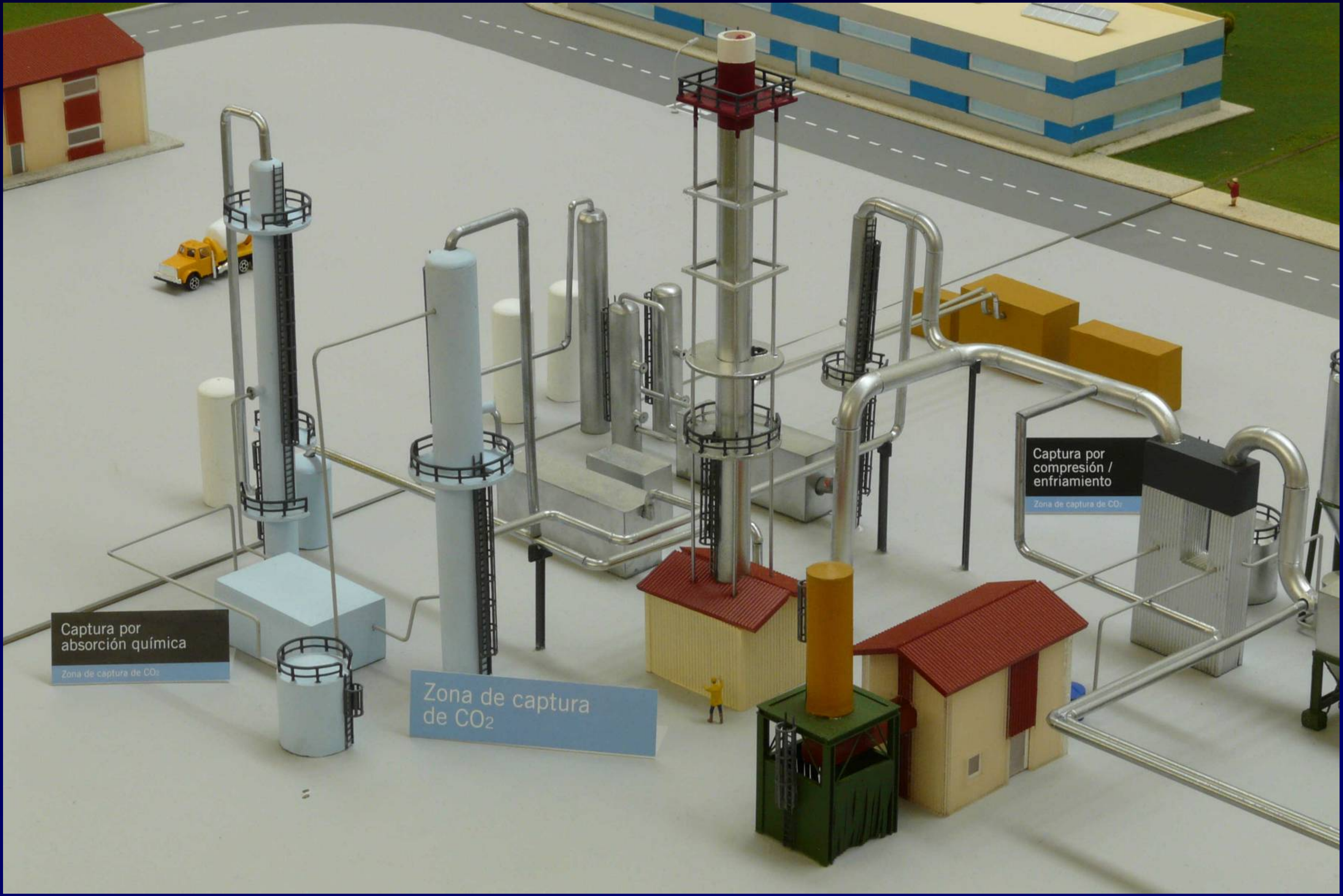
Combustion island and O_2 supply

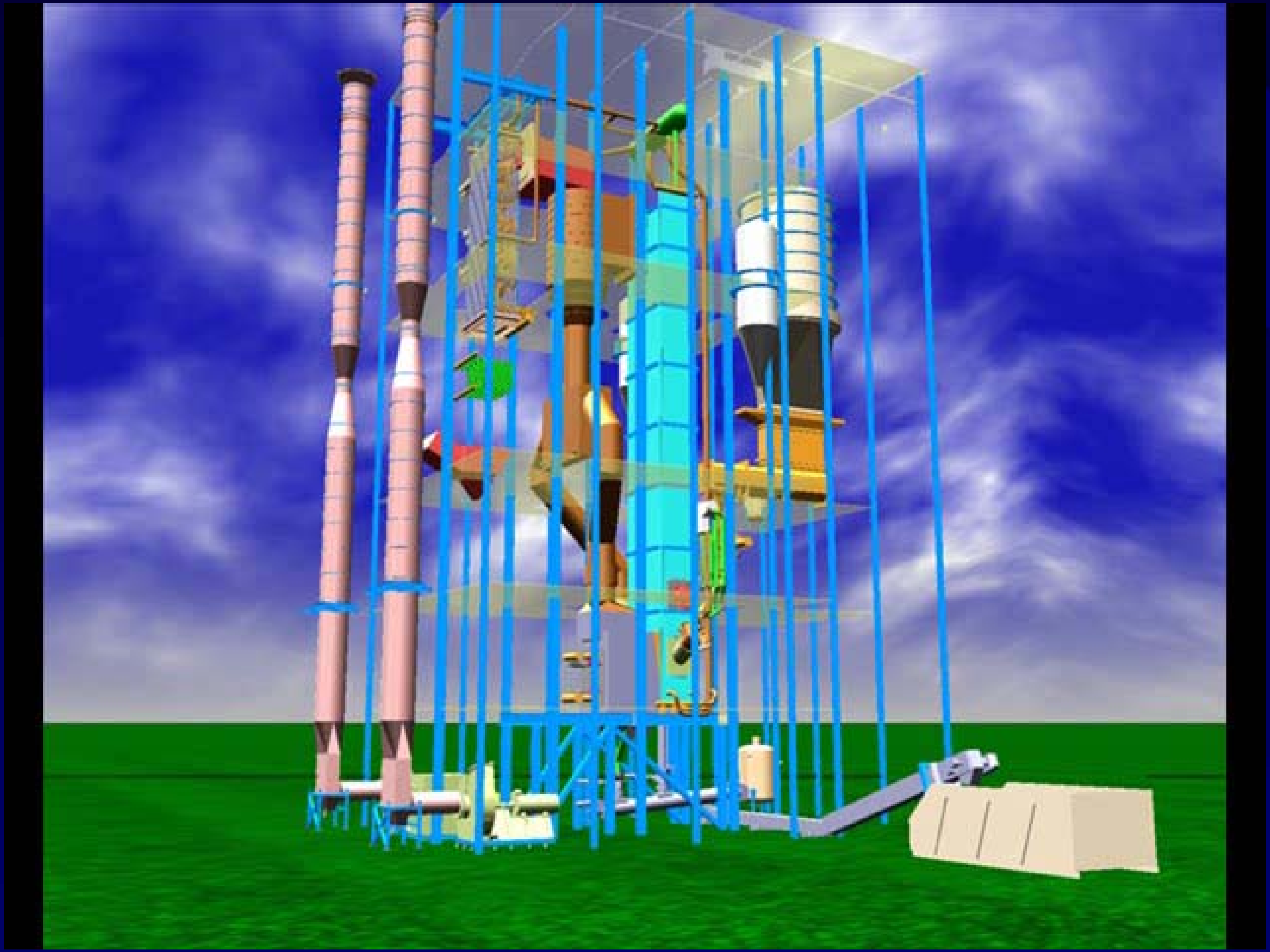
Flue gas cleaning section



CO_2 capture section



CFB by Foster Wheeler



ciudad de la energía

Gobierno de España

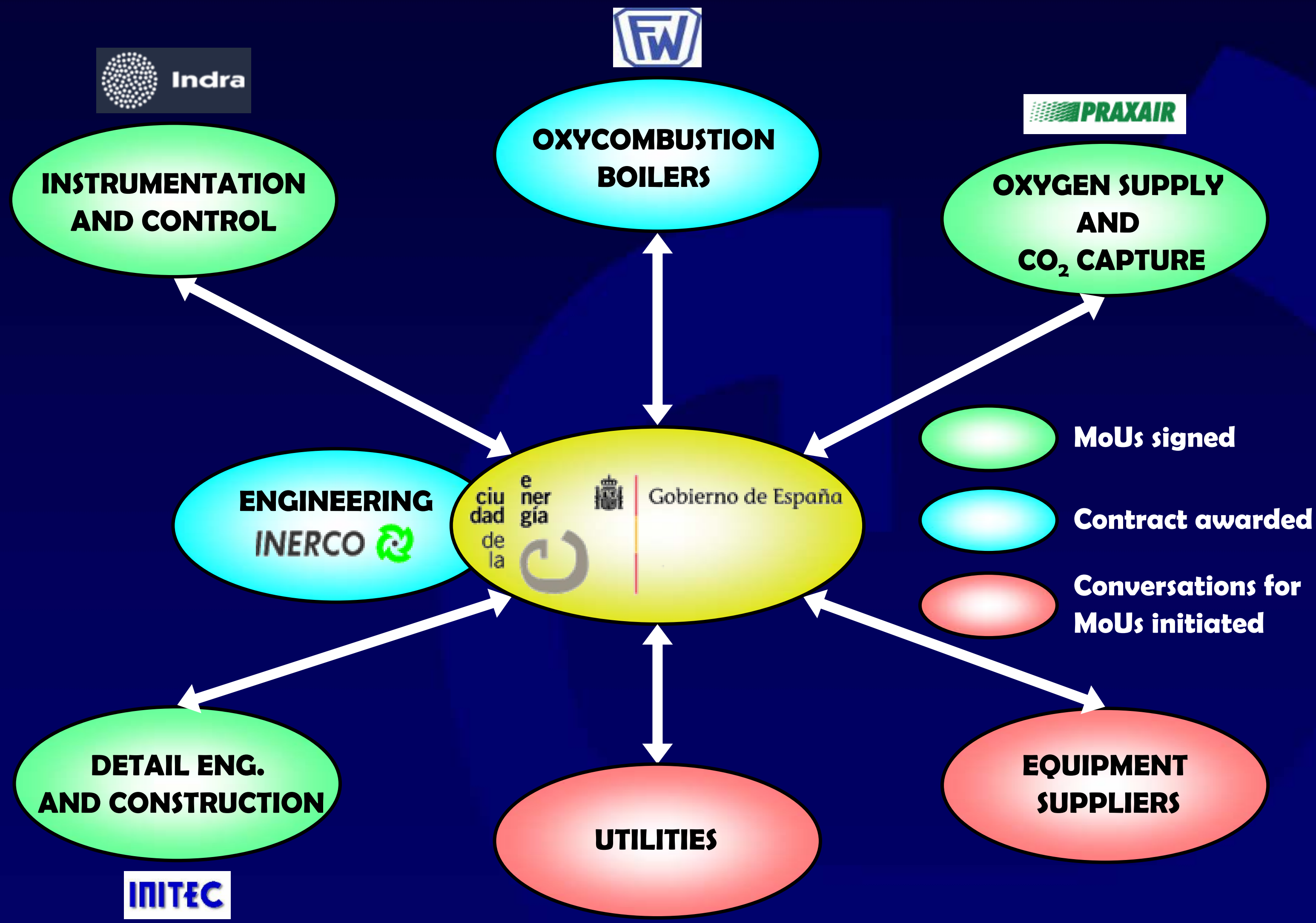
TEST FACILITY FOR CO_2 CAPTURE TECHNOLOGIES EL BIERZO

Project Structure

Prof. Dr. V. J. Cortés

TEST FACILITY FOR CO_2 CAPTURE TECHNOLOGIES EL BIERZO

Project structure



Research program

Prof. Dr. V. J. Cortés

The R&D programme structure

RESEARCH PROGRAMME OF EL BIERZO TEST FACILITY

SCIENTIFIC PROGRAMME

PROMOTED BY CIUDEN AND PERFORMED BY RELEVANT SPANISH RESEARCH INSTITUTIONS

EXPERIMENTAL PROGRAMME

PERFORMED AT THE FACILITY IN COOPERATION WITH RESEARCH INSTITUTIONS, TECHNOLOGY PROVIDERS AND TECHNOLOGY USERS

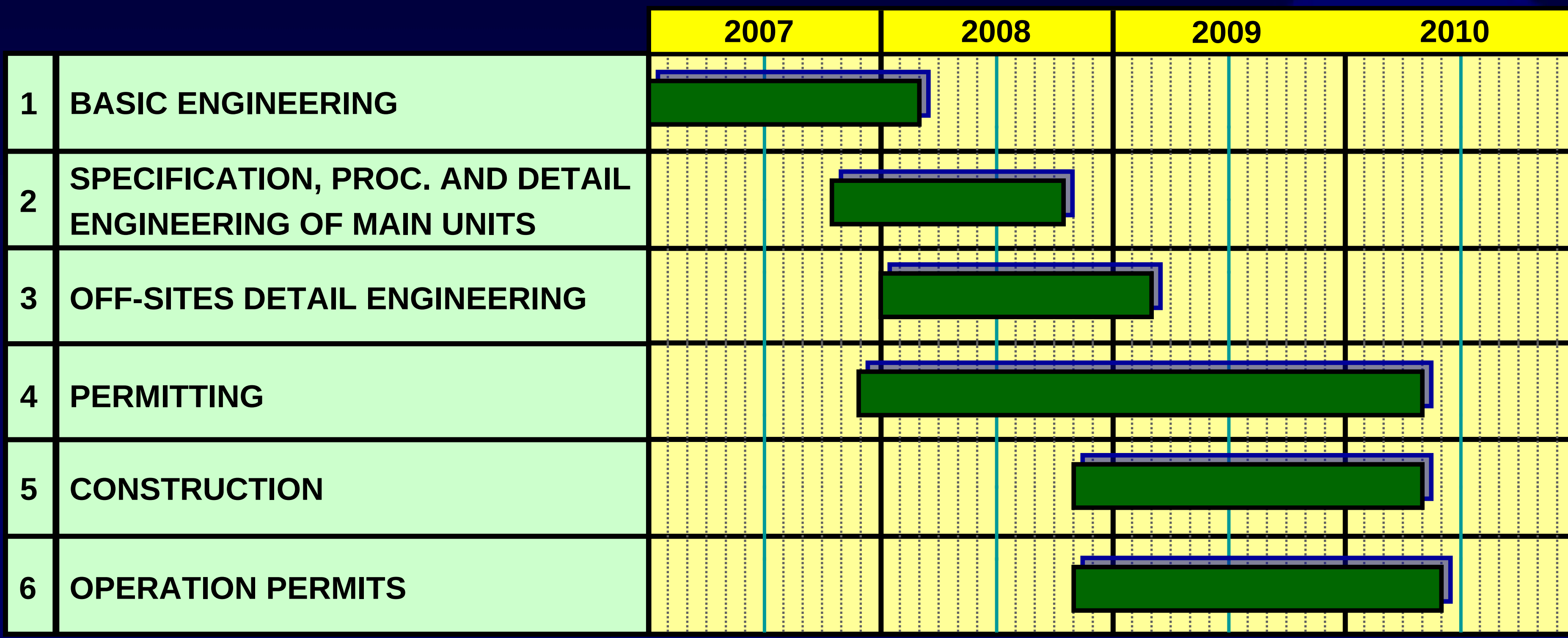
Experimental Programme

TARGETS

- ✓PROCESS PERFORMANCE IN CONTINUOUS, PART-LOAD OPERATION AND LOAD FOLLOW-UP
- ✓VALIDATION OF ENGINEERING AND DESIGN TOOLS AND PROCESS MODELS FOR SCALE-UP

Time schedule

Time schedule



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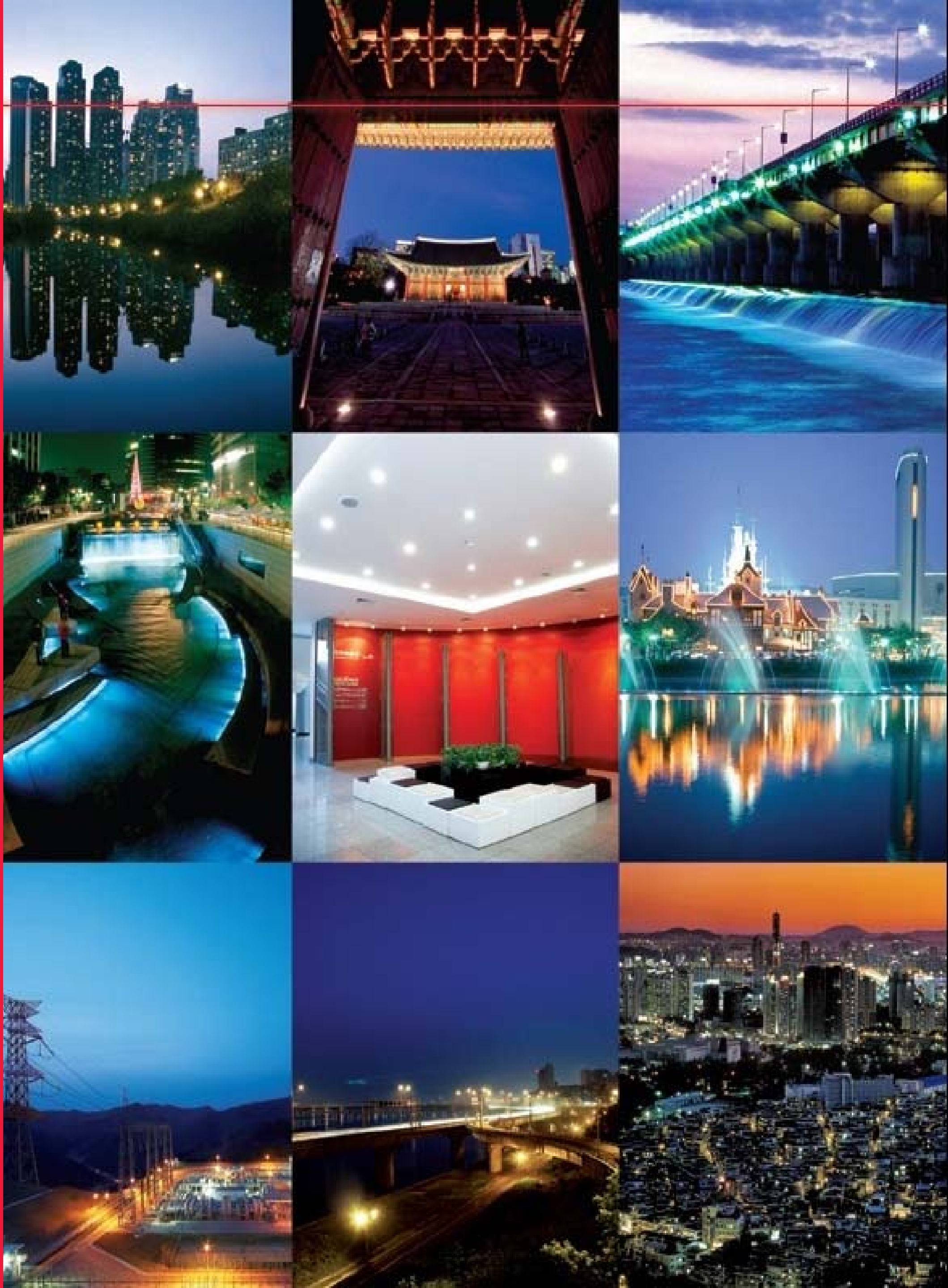
TEST FACILITY FOR ADVANCED TECHNOLOGIES FOR CO_2 CAPTURE IN COAL POWER GENERATION

UPDATE AND UPGRADE

Prof. Dr. Vicente J. Cortés
CO_2 Capture Program Director
CIUDEN, SPAIN

Oxy-Combustion Research Activities in Korea –

An Overview to the Youngdong 100MWe Oxy-Combustion Power Station Project Demonstration



Oxy-Combustion Research Activities in Korea

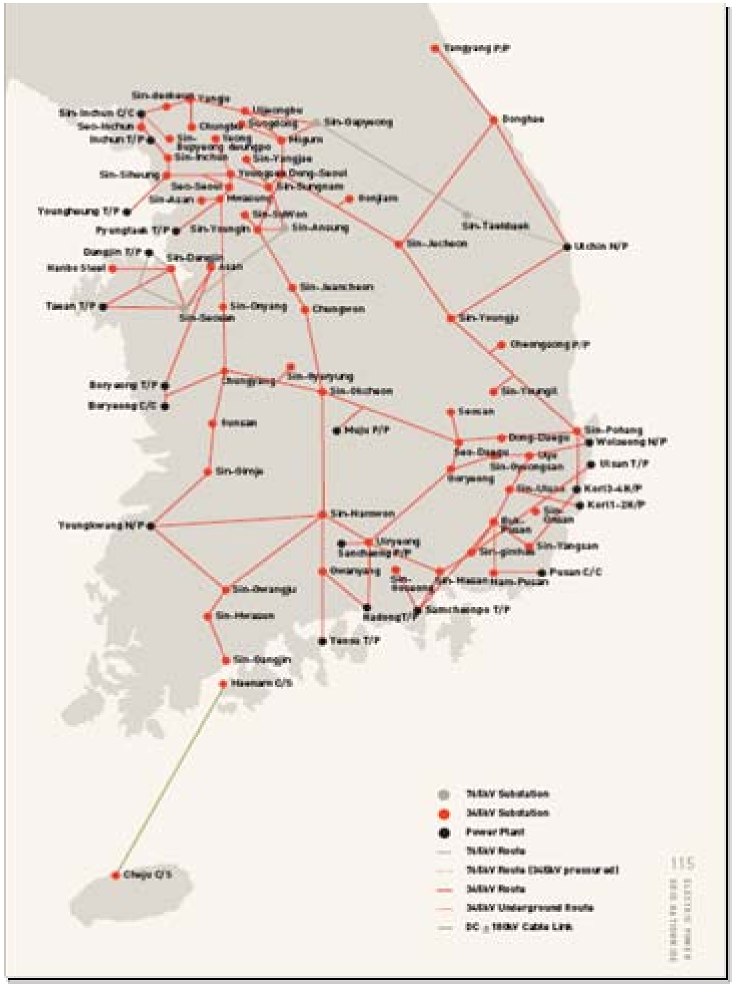
An Overview to the Youngdong 100MWe Oxy-Combustion Power Station Project Demonstration

Jong Soo Kim[1], Sangmin Choi[2], Youngju Kim[3] and Sung Chul Kim[3*]

1 : Korea Institute of Science and Technology
2 : Korea Advanced Institute of Science and Technology
3 : Korea Electric Power Research Institute
** : Project Leader*

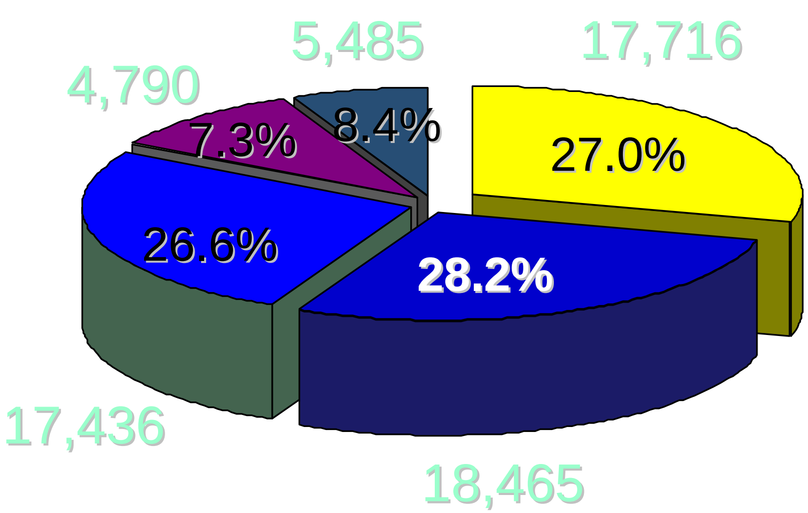
Electric Power Companies

Korea Electric Power Corp. (KEPCO)	Mother Company Transmission & Distribution Oversea Business
Hydro & Nuclear Power (KHNP)	Hydro (0.5GW) & Nuclear (17.7GW)
Korea South-Eastern Power (KOSEP)	Thermal Power Generation - Steam : Coal & Oil - NGCC - CHP - 8~9 GWe for each comp. 6 Main Coal Power Stations - 6~10 units per site - One site each company - **KOSEP operates 2 sites**
East-Western Power (EWP)	
Western Power (WP)	
Korea Middle Power (KOMIPO)	
Southern Power (KOSPO)	
Korea Power Engineering Co. (KOPEC)	Engineering Company
Korea Electric Power Research Inst. (KEPRI)	KEPCO R&D Wing



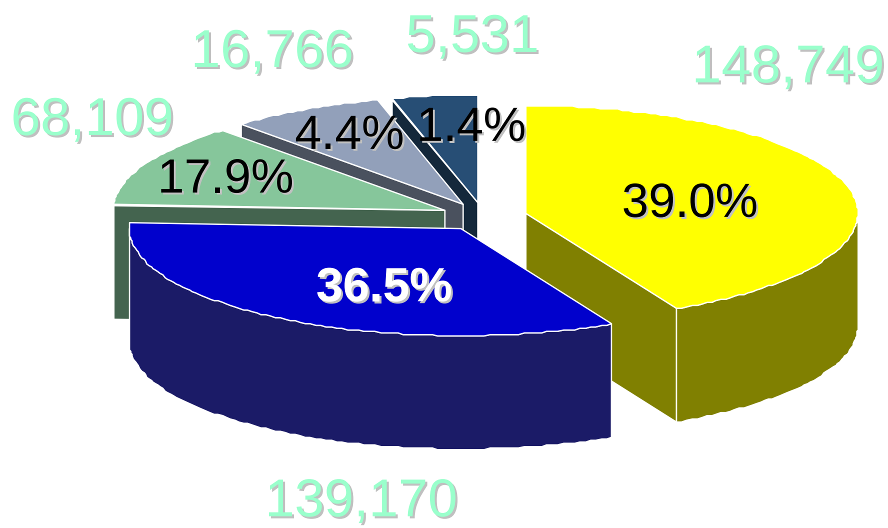
Power Capacity & Generation (2006)

Plant Capacity



Total: 65,514 MW

Power Generation



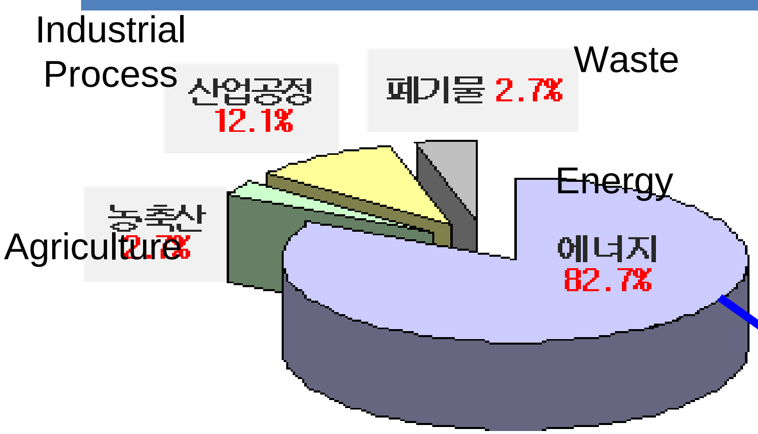
Total: 380,964 GWh

Nuclear	Coal	Gas	Oil	Hydraulic

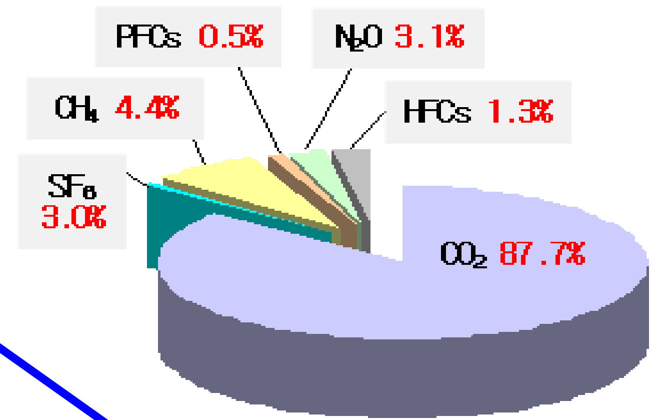
- Mass/Alternative Power Capacity: 1,622MW
- Mass/Alternative Electric Power Generation : 2,939GWh

GHG Emission in Korea

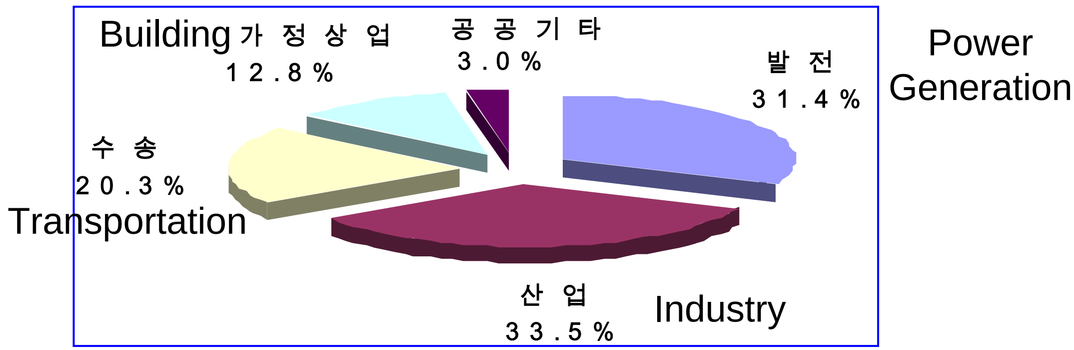
Emission by Sector



Emission by GHG



- ❖ Electric Power Sector
  - ➢ 150 MtCO2/Annum
  - ➢ 25% of GHG Emission
- ❖ Coal Firing Power
  - ➢ 115 MtCO2/Annum
- ❖ 3.2MtCO2/500MWe
  - ➢ 10,000tCO2/day
  - ➢ 0.5% of National GHG Emission



Energy Sector

Key Technology Development in KEPCO

- ❖ Nuclear Power Generation
- ❖ High Efficiency PC Power Generation
  - ➢ USC Power Generation Technology
- ❖ CO_2 Capture from Thermal Power Plants
  - ➢ Post-Combustion Capture
    - ◆Wet-Scrubbing : Amine Scrubbing (Currently 1TPD)
    - ◆Dry-Scrubbing
  - ➢ Pre-Combustion De-Carbonization
    - ◆IGCC (300MWe) Construction by 2014 : without CO2 Capture
  - ➢ Oxy-Fuel Combustion
    - ◆100MWe Demonstration by 2018

Trend of the Standardized Coal Plants

500MW
- 500 MW, 41.1%, 246kg/cm2g, 538/541℃
- 24 units in service since 1984

500USC
- 519MW, 43.5%, 246kg/cm2g, 566/593℃
- 2 units in service since 2006, 8 units u.c.

800MW
- 814(886)MW, 43.5%, 246kg/cm2g, 566/566(593)℃
- 2 units in service since 2004, 2 units u.c.

1,000MW
- **1,000MW, 45%, 265kg/cm2g, 610/620℃**
- **Expected in service in 2015**

Summary of the Progress- 2007
Korean Oxy-PC Project

- Oxy-Fuel Combustion R&D
  - Started in 2002 for Oxy-NG Combustion in Industrial Furnaces
  - Small Scale Oxy-Coal Combustion R&D from 2006 by CDRS
- New MOCIE Energy R&D Program
  - 10 New Research Areas Proposed (2006)
  - Planning Writer : J. S. Kim for CCS by Oxy-Combustion
    - Planning Report Submitted in May 2007.
- National R&D Program Led by the KEPRI group
  - Launched in October 2007
  - Industrial Participants
    - KOSEP
    - Daesung Industrial Gas
    - Korea Cottrel
  - Tentative Demonstration Site : Youngdong Power Station Unit #1

Why Oxy-Fuel ?

- Competitive Performance
  - Efficiency Penalty : 8% (depending on system configuration)
  - Cost of CO_2 Capture : Less than 20€/tCO_2 Possible
- Complete Separation of CO_2 Possible
  - Perhaps Necessary for Deep Cut in CO_2 Emission
- Improved Fuel Flexibility
- Key Technologies Available
  - Oxygen Production, Combustion, Boiler, …

- Higher Level of Integration Needed

Oxy-PC Technology Development Plan

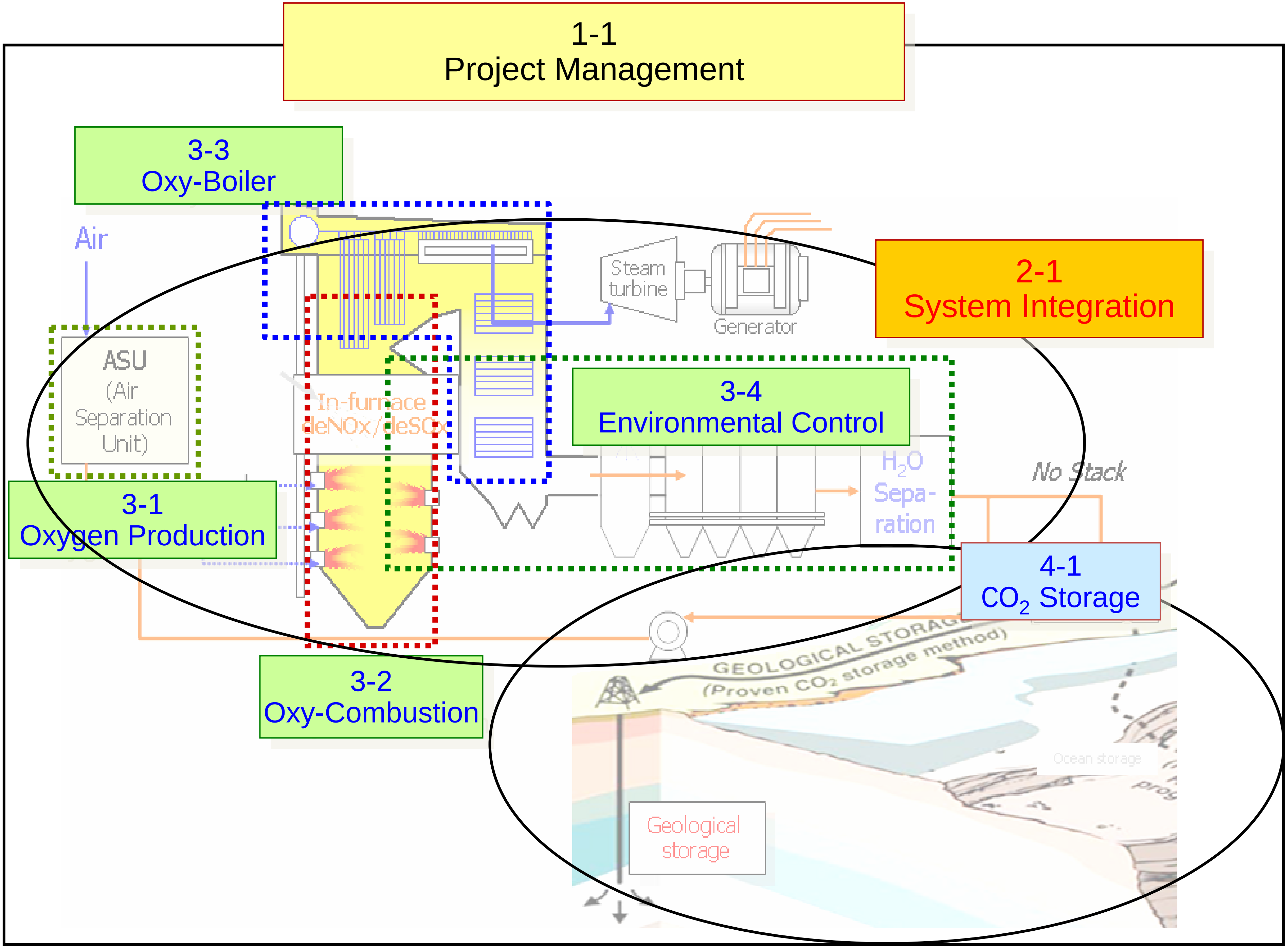
- Phase I (2007~10) Research and Conceptual Design Development
- Phase II (2010~13) Basic/Detailed Design of a Demo Plant
- Phase III (2013~15) Construction of Demo Plant

Plant Conceptual Design – KEPRI
- KOSEP, Daesung Indust. Gas
- Design Concept for Optimum Operation

Boiler & Combustion – KEPRI/KITECH
- KOSEP
- Boiler & Burner Development

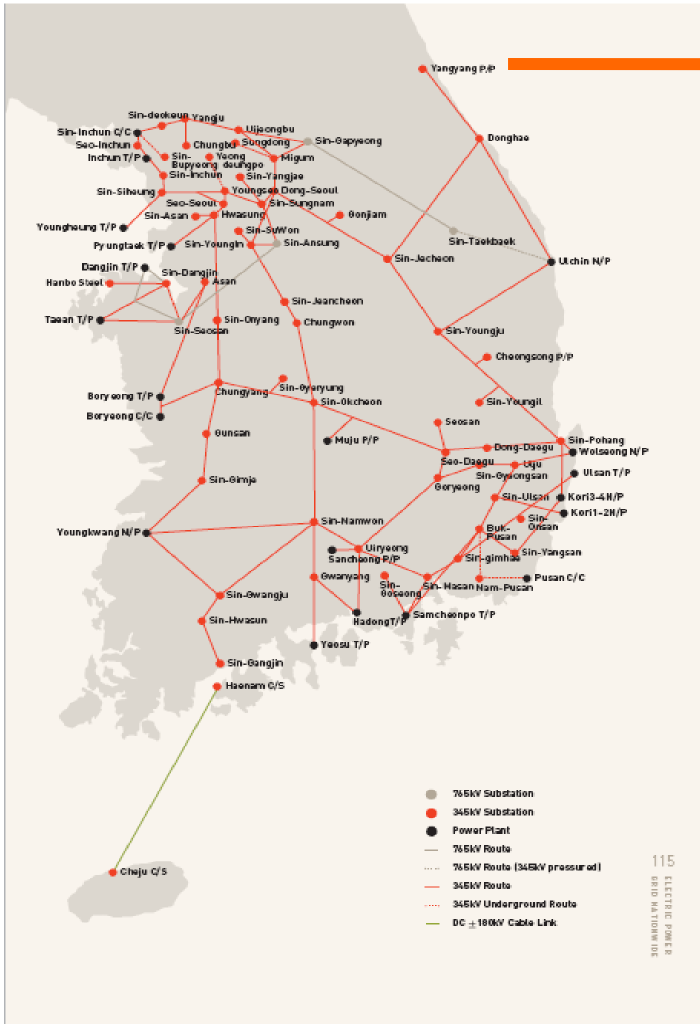
Environmental Control – KIMM
- KOSEP, Korea Cottrel
- Flue Gas Cleaning for Plant Maintenance

CO2 Storage – KIGAM
- Fundamental Study, CSLF : Otway Bay Project


1-1
Project Management
3-3
Oxy-Boiler
Air
ASU
(Air Separation Unit)
Steam turbine
Generator
2-1
System Integration
In-furnace deNOx/deSOx
3-4
Environmental Control
H_2O Separation
No Stack
3-1
Oxygen Production
4-1
CO_2 Storage
GEOLOGICAL STORAGE
(Proven CO_2 storage method)
Ocean storage
Geological storage
3-2
Oxy-Combustion

KOSEP

Proposed Demonstration Project



- Replacing the Youngdong unit #1
  - Current : 125MWe w. Domestic Anthracite
  - Decommission by 2013
  - Oxy-Fuel Repowering
- 100MWe Class Demonstration
  - Design by 2013
  - Construction by 2015
  - Demonstration : 2016~2018

KEPCO KOREA ELECTRIC POWER CORPORATION

KEPRI

Youngdong Opportunity

- ❖ Youngdong Power Station
  - ➢ Unit #1 : 125MWe
  - ➢ Unit #2 : 200MWe
  - ➢ Coal Type : Domestic Anthracite (Heavily Subsidized)
- ❖ Oxy-Fuel Opportunity @ Youngdong Unit #1
  - ➢ Coal Supply for unit #1 : End by 2013
  - ➢ MOEnv will not Renew the Environmental Permit for the Current Unit
    - ◆ New Unit is Necessary
  - ➢ KOSEP Intends to Convert the Unit #1 for Oxy-Fuel Option
    - ◆ Coal Type : Sub-Bituminous (Low Sulfur)
    - ◆ Optimize the Power Production Cost
    - ◆ Almost "Greenfield" Construction

Issue of Fuel Flexibility

- Increased Use of Sub-Bituminous Coal in Korea
  - Sub-Bituminous : Blending with Bituminous Coal
  - Cheaper
  - Higher Moisture, Dust & Volatiles
  - Low Ash Fusing Temperature
  - Low S & N
- Advantages of Oxy-Combustion for the Sub-Bituminous

Coal Characteristics	Oxy-Combustion Advantages
Tendency toward Explosion/Fire	Recycled Flue : Inert PC Carrier
High Slagging	Lower Flame Temperature
Low S & N	Simpler Environmental Control

Project Objectives

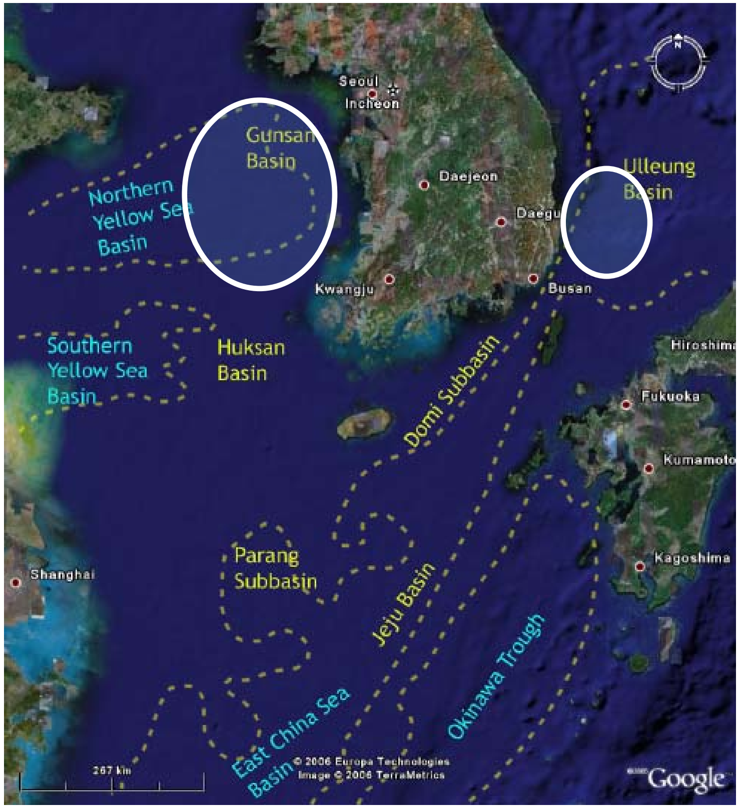
- ❖ Demonstration of Oxy-Fuel Operation by 2018
  - ➢ Oxy-Fuel Repowering by 2015
- ❖ Target Coal Type : Sub-Bituminous
  - ➢ Improved Fuel Flexibility
- ❖ Optimize the Power Generation Cost
  - ➢ Minimize the Efficiency Penalty : 8%
  - ➢ Minimize the Plant & Environmental Cost
    - ◆ No SCR, FGD (Possible ?), Stack
  - ➢ CO_2 Capture Cost : Less than 20€/tCO_2

Technological Objectives

- Performance Optimization
  - Management of Incondensibles (Ar, N_2, O_2, …)
  - Combustion
    - Low NOx & Excess O_2 Combustion
    - Boiler Start Up : Additional Fuel Saving by Oxy-PC Start Up
  - Boiler Optimization : Capture Ready Possible ?
- Plant & Environmental Cost
  - Bypass SCR & FGD
    - Dry DeSOx Process : Combined with Low S Coal Type & Hybrid EP
- CO_2 Treatment
  - Currently No Full Scale CO_2 Storage Possible
  - Main Concern
    - Post Capture Treatment (Purification & Compression)
    - Utilization of the Captured CO_2

Future Uncertainties

- ❖ Deregulation of the Power Market
  - ➢ Need to see how the circumstances unfold
- ❖ Increased Fuel Cost
  - ➢ Constricted Cash Flow Stream from the Power Companies
- ❖ International CCS Regulations
- ❖ How to Achieve the Capture Readiness
  - ➢ Do we have to go for the direction of CFB ?
- ❖ Weak Storage Resources
  - ➢ No Confirmed Storage Resources Yet !
  - ➢ Possibility in Saline Aquifers
  - ➢ West & South-East Coasts



Thank You

Oxy-Coal Combustion Demonstration Project

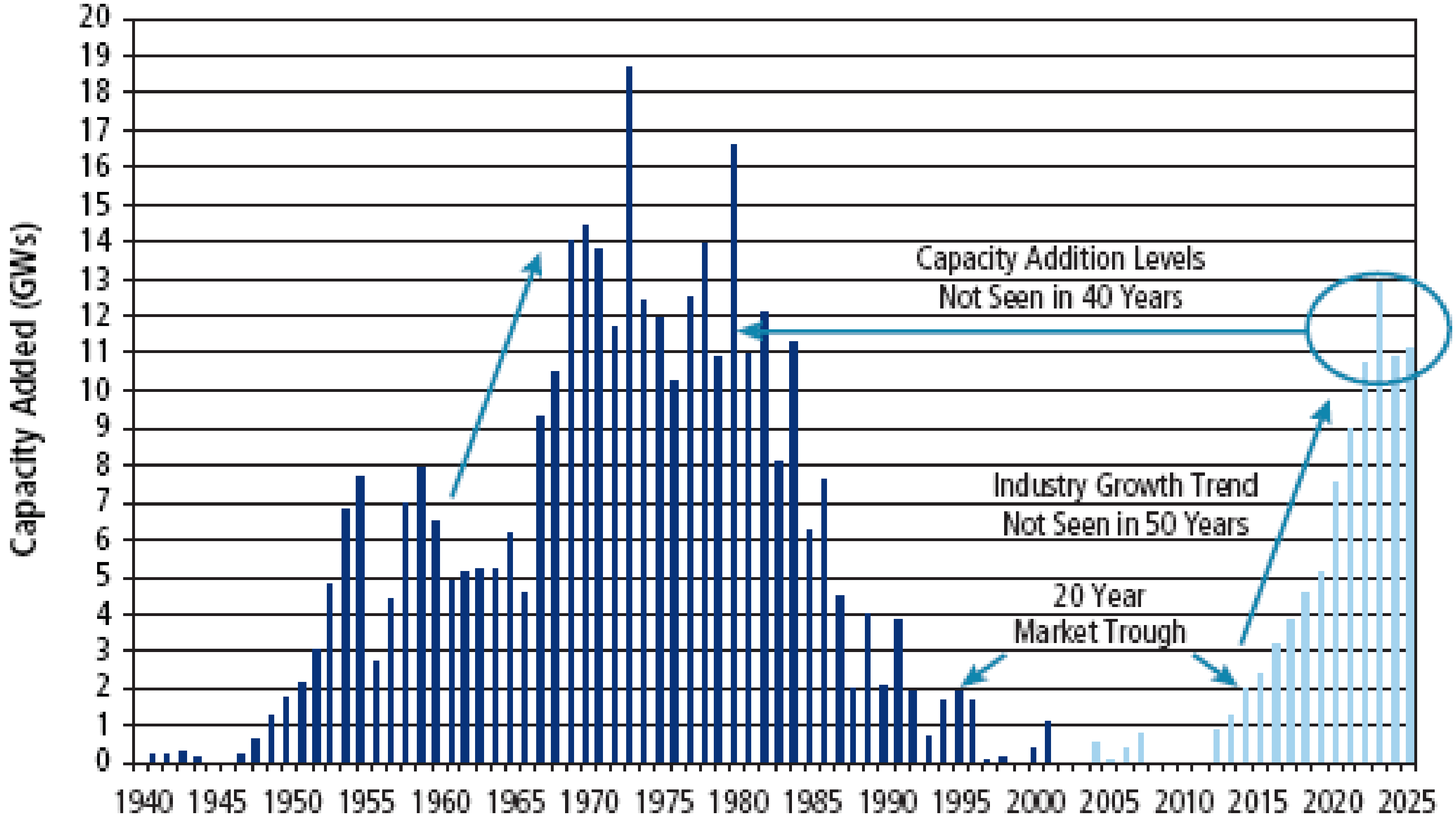
Dante Bonaquist, Rick Victor and Minish Shah (Praxair), Horst Hack and Arto Hotta (Foster Wheeler), Dave Leathers (Jamestown BPU)

IEAGHG International Oxycombustion Network – 3rd Workshop

Yokohama, Japan

March 5 – 6, 2008

U.S. Coal Capacity and CCS Potential



Source: DOE, NETL 2006

Up to 100 GW of coal capacity with CCS in next 25 years
ASU + CPU potential $2 - $3 Bn/yr

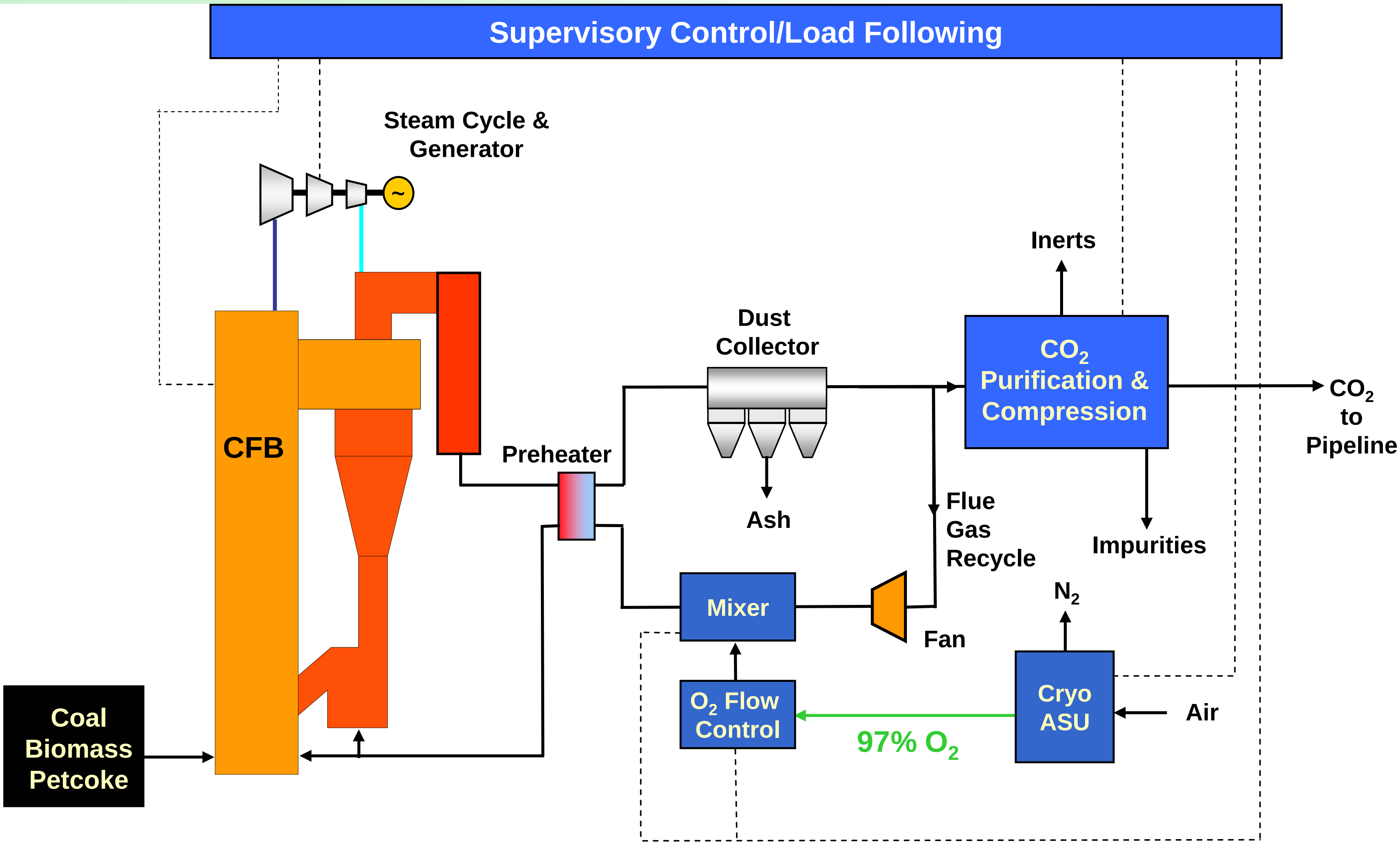
Objectives of Demonstration

PRAXAIR
FOSTER WHEELER

- Demonstrate fully integrated CCS project
- Employ advanced technologies
  - CFB Boiler
  - ASU and CO_2 processing unit
  - System integration
- Prove reliability and availability
- Operate with typical load factor variations
- Learn transient modes of operations

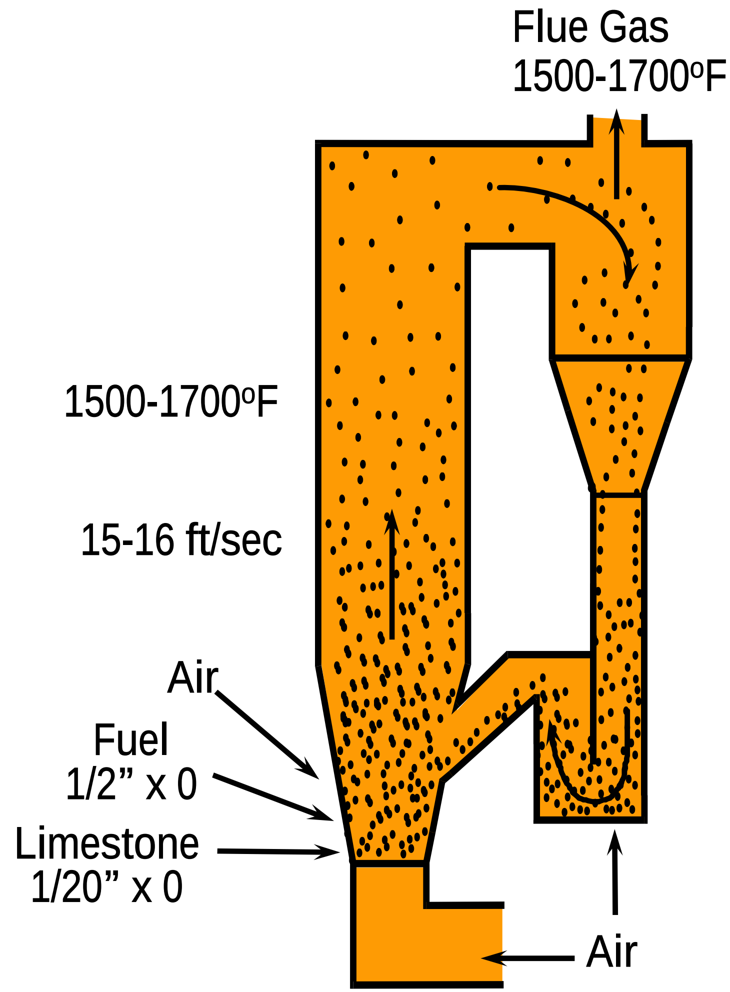
Enable Direct Scale-Up to a Commercial CCS Operation

Oxy-Coal CFB Power Plant

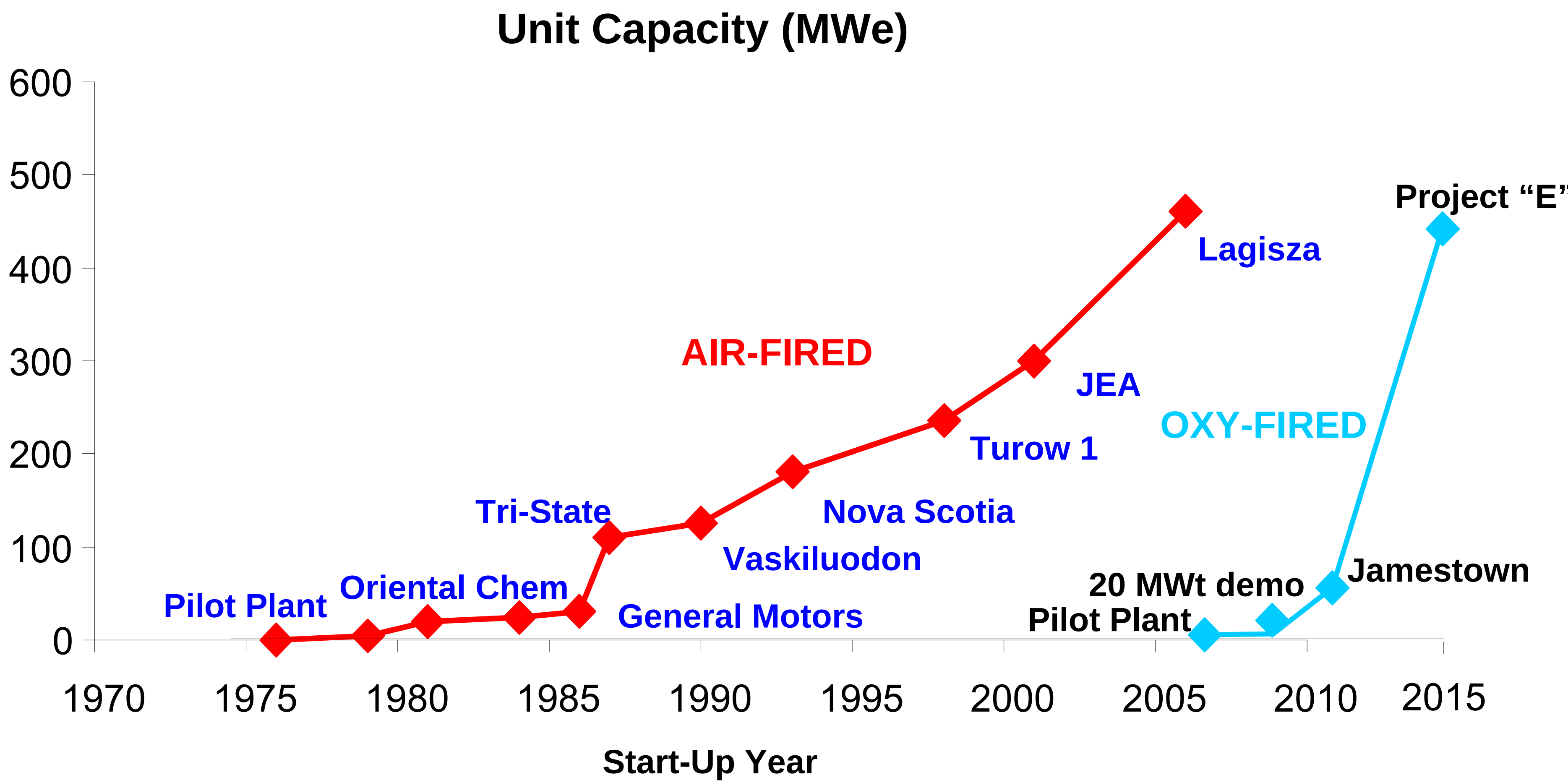


Circulating Fluidized Bed Process Advantages

Feature	Benefit
Low furnace temperatures	- Low NO_x - In-bed SO_2 capture -Fuel flexibility (Biomass) - Ideal for Oxy-coal CCS
Hot circulating solids	- Tolerant to fuel variations - Efficient heat transfer - Simple feed systems - Uniform heat flux - Ideal for SNCR
Long solid residence time	- Good fuel burnout - Good sorbent utilization



Foster Wheeler CFB Experience



CFB Process Scale-up and Modularization

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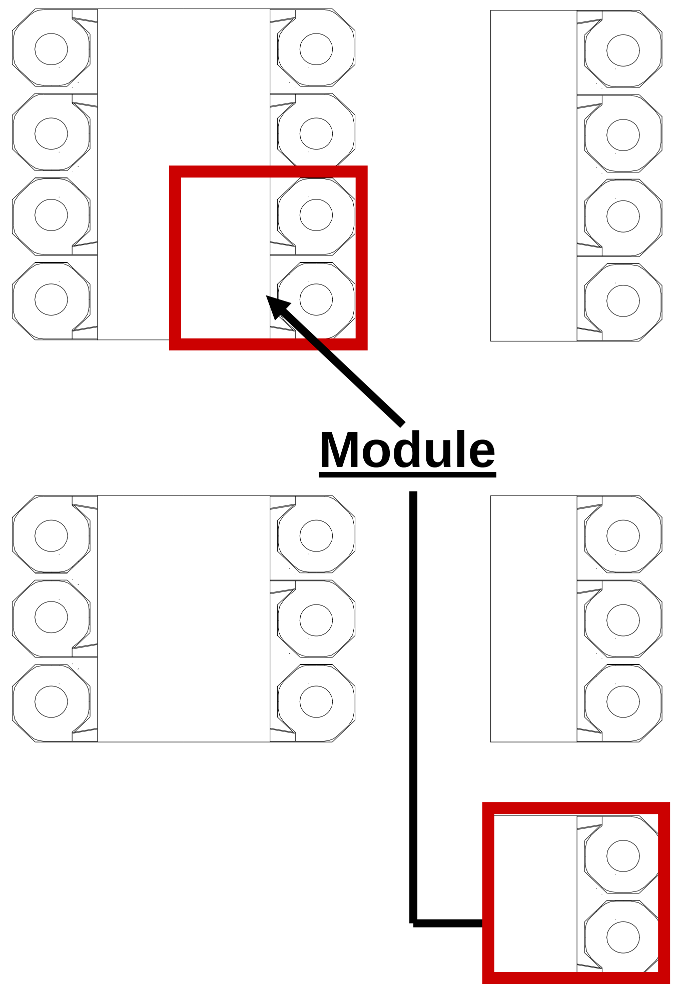
FOSTER WHEELER

400-600 MW_e

200-300 MW_e



300-400 MW_e

150-200 MWe

50-100 MW_e

Demonstration will enable scale-up to 600 MWe

Success Factors for Demonstration

- Proximity to a suitable geologic CO_2 storage site
- Advanced coal power plants that capture and store CO_2
  - All plant components are advanced and scalable
  - All learnings applicable to retrofit applications
- Availability of financing for capital investment
  - Base plant investment on a commercial basis
  - CCS investment funded by government
- Project timing on a fast track
  - 2013 start-up
- World class technology and project execution team
  - Boiler island, ASU and CO_2 processing, sequestration & environmental permitting

Jamestown BPU Background

- Existing PC plants are reaching the end of their useful life.
- Proposed replacement with CFB boiler
  - SO_2 - 94% reduction
  - NO_x - 89% reduction
  - Hg - 95% reduction
  - CO_2 - 20% reduction
  - Ability to fire biomass, petcoke and TDF
- Oxy-fuel combustion significantly enhances environmental performance
  - CO_2 mitigation plan required to obtain permit in NY state

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Advanced Integrated Dual-Oxidant CFB Power Plant with CCS
"Oxy-Coal CFB"

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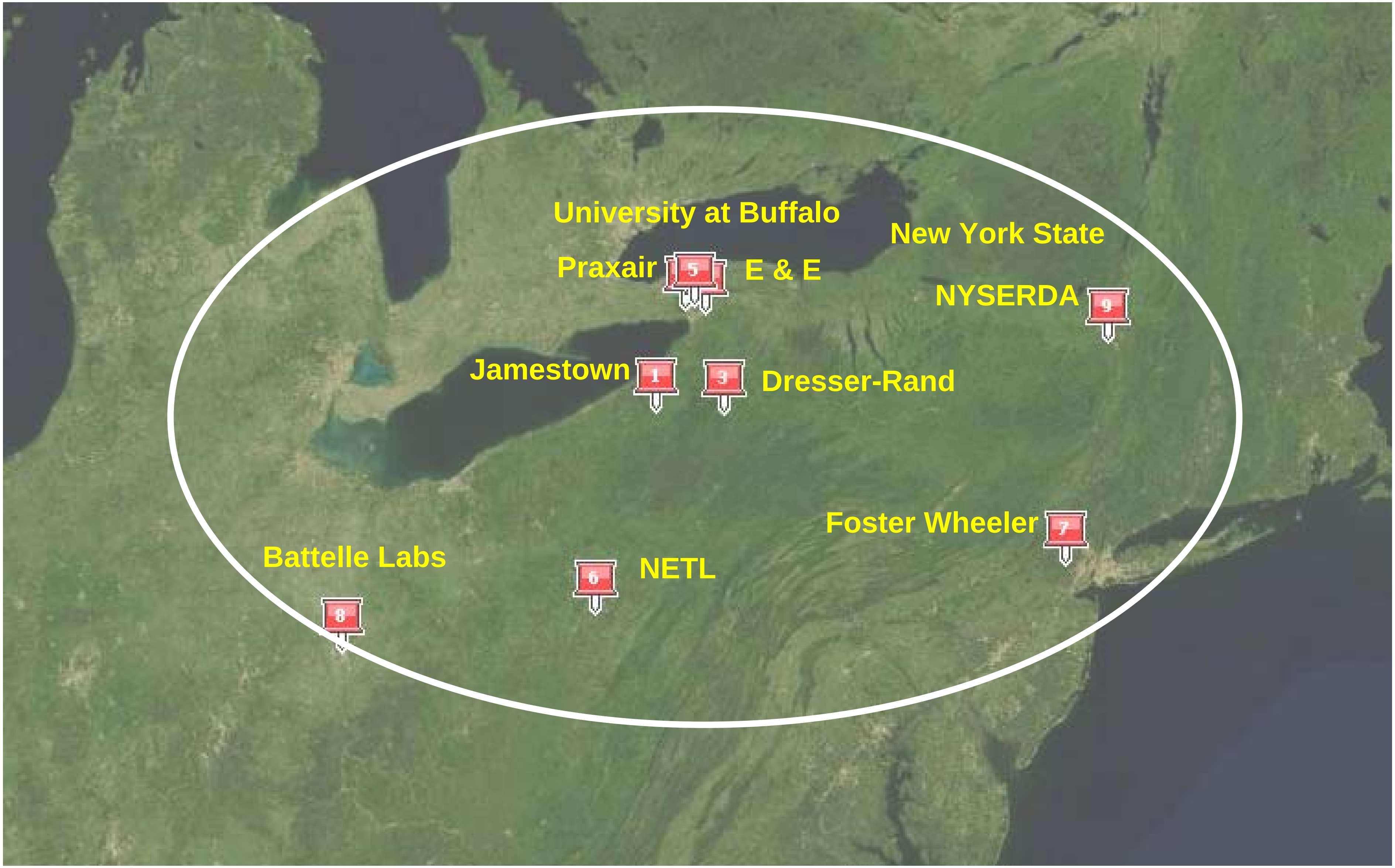
Battelle
The Business of Innovation

DRESSER-RAND

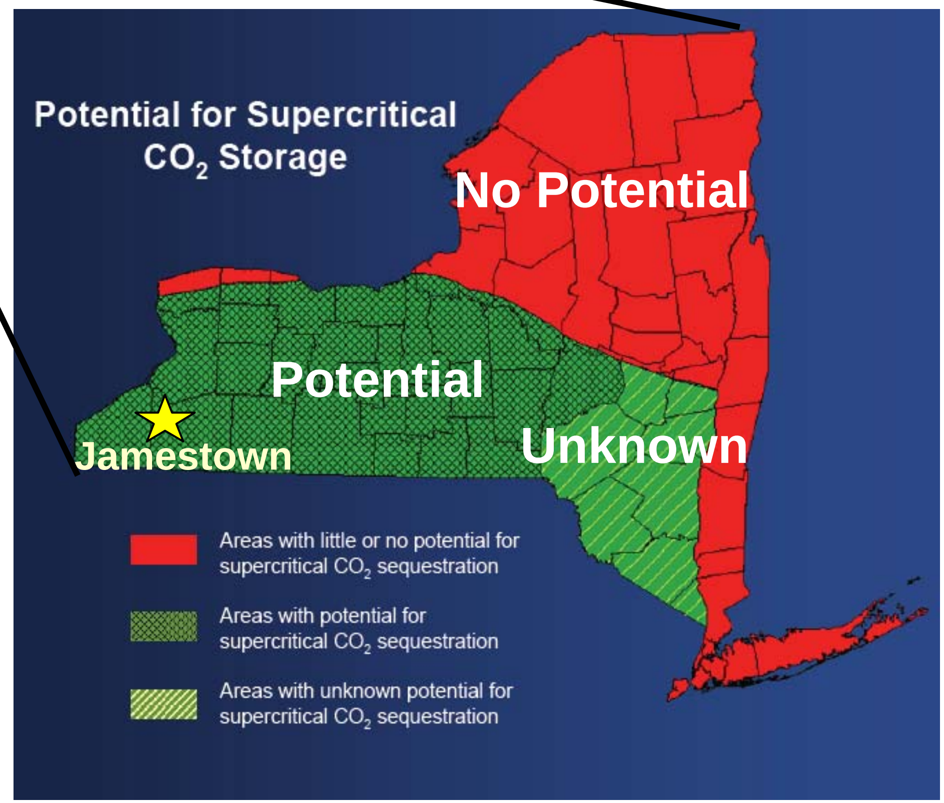
U.S. Oxy-Coal Technology Campus



Jamestown BPU Power Plant Site

Potential CO_2 Storage at Jamestown

Source: Natcarb.org

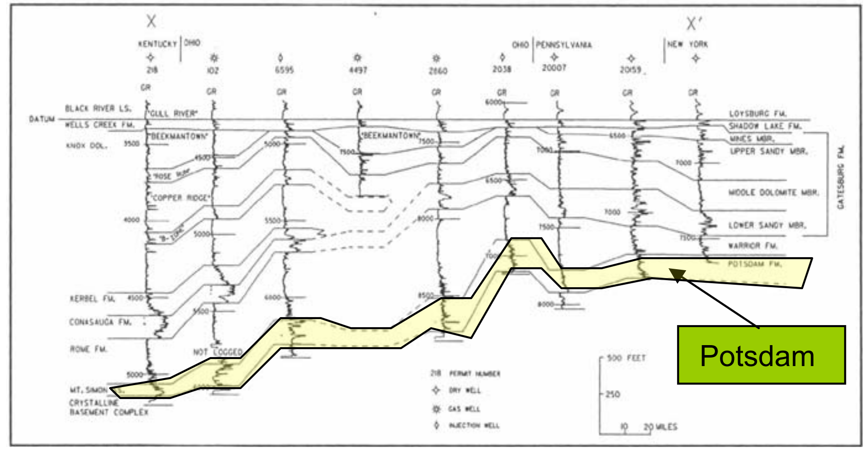


Source: NYSERDA

Jamestown Area - Preliminary Analysis of Sequestration Targets

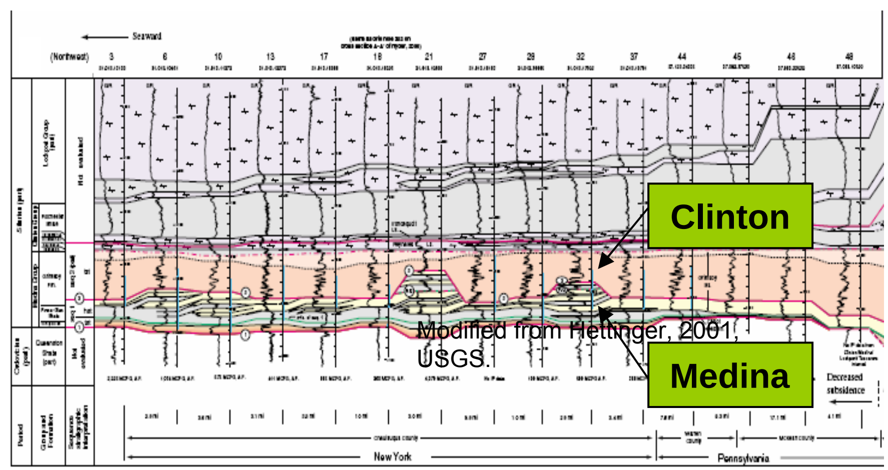
Potsdam Sandstone

-The Potsdam Sandstone is the basal sand in SWNY
-Depth of about 7,000 ft
-Thickness ranges from approx. 100-250 ft
-Possible seal would be the Utica Shale
-Additional storage potential may be present in overlying Theresa Formation carbonates



Clinton-Medina Group

-Commonly produces gas in Chautauqua Co.
-Average depth is between 3,000 and 5,000 ft
-Thickness ranges from approx. 50-100 feet
-Possible seal in shales of the Hamilton Group



NYSERDA Sponsored Study Planned to Identify Well Locations

Source: Battelle

Project Timeline

- Q2 2008 Preliminary feasibility study
- Q4 2008 NYSERDA feasibility study for sequestration
- Q1 2009 Funding for the project secured
- Q1 2010 Detailed design completed
- Q1 2010 Begin Oxy-coal CFB construction
- Q1 2013 Oxy-coal CFB Start-up

Challenges

- EPA regulatory framework for CCS
  - Air and CO_2 injection permits
- CO_2 liability
- Cost of operating CCS beyond demonstration
- Value for CO_2
- Government budget to support CCS demonstration

Summary

- 50 MWe demonstration project planned to enable direct scale-up to a commercial unit
- Jamestown BPU project selected for demonstration
- Significant challenges ahead
- Technology roadmap is clear
- The commercial roadmap is getting clearer
- Regulatory roadmap will provide clarity

The time is now for fully integrated CCS demonstration