Challenges in the Development of
Oxy-Coal Combustion Power Plant with CO₂ Capture

by
Stanley Santos

Asia Pacific Programme (APP)
Oxyfuel Working Group Capacity Bldg. Course

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*Corresponding Author’s Email: stanley.santos@ieaghg.org

http://www.ieagreen.org.uk
Outline

• Introduction
• Oxy-Coal Combustion Power Plant with CO₂ Capture
  o Historical perspective & the development with respect to its future commercial deployment
• Challenges in the development of oxy-coal combustion boiler
• Challenges in the development of oxygen production
• Challenges in the CO₂ processing and compression
  o Overview and update to some of the large scale oxyfuel combustion pilot and demonstration projects
• Conclusions
All IEA Scenarios require CCS on both coal and gas power plants.
Energy Innovation Chain:
Research, Development, Demonstration and Deployment

Feedback of R&D needs

Research & Development
- Basic R&D:
  - speculative, science led
  - industry needs led
- New Ideas
- Pilot Plant Constructed

Demonstration
- applied R&D to address technical issues
- underpinning R&D to mitigate perceived technical, market & financial risks
- First Full-Scale Plant Operational

Deployment
- Product Considered “Commercially Proven” - 100’s of MW (equivalent) deployed

Several companies and their associates are involved in a wide range of R&D and seeking to move to Demonstration and plan for Deployment
ANL/Battelle/EERC completed the first industrial scale pilot plant

1980’s

1990 – 1995

EC Joule Thermie Project
  • IFRF / Doosan Babcock / Int’l Combustion
  • NEDO / IHI / Jcoal Project

1998 – 2001

Vattenfall (ENCAP ++) / CS Energy / IHI Callide Project

2003 - 2005

B&W CEDF (30MWt) large scale burner testing started

2007

Vattenfall’s Janschwalde (250MWe)
KEPCO/ KOSEP - Yongdong (100MWe)
FW/Praxair - Jamestown (50MWe)
Endessa (500MWe)

World’s FIRST 30 MWt full chain demonstration at Schwarze Pumpe – started operation

By 2014-2016
Demonstration of 50– 500MWe full scale power plant.

By the end of 2009/2010, Users (i.e. Power Plant Operators) will have 6 burners manufacturers fully demonstrating “Utility Size Large Scale Burners” which should give a high level of confidence in going to the next step

Target: “Commercialised by 2020”

B&W CEDF 2008 30MWth Coal
Alstom Alstom 2010 15MWth Coal
Doosan Babcock DBEL - MBTF 2009 40MWth Coal

Alstom Schwarze Pumpe 2008 30MWth Lignite
Hitachi Babcock Schwarze Pumpe 2010 30MWth Lignite
IHI Callide 2010 30MW Coal
Alstom / AL Lacq 2009 30MWth Gas/Oil?
FW - CIUDEN Ibierza facility 2010 15Mwth Coal
FW - CIUDEN Ibierza facility 2010 20Mwth Coal

First large scale 35MWt Oxy-Coal Burner Retrofit Test done by International Combustion
Oxy-Fuel Combustion Boiler Projects
(Conversion @ 1 MWe = 3 MWt = 10 MMBtu/hr)

Utility Boilers

Industrial Furnaces

Test Furnaces

Year

MWe
## Large Scale Pilot and Demo Projects

<table>
<thead>
<tr>
<th>PROJECT</th>
<th>Location</th>
<th>MWth</th>
<th>Start up</th>
<th>Boiler Type</th>
<th>Main Fuel</th>
<th>CO2 Train</th>
</tr>
</thead>
<tbody>
<tr>
<td>B &amp; W USA</td>
<td>USA</td>
<td>30</td>
<td>2007</td>
<td>Pilot PC</td>
<td>Bit, Sub B., Lig.</td>
<td></td>
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<tr>
<td>Jupiter USA</td>
<td>USA</td>
<td>20</td>
<td>2007</td>
<td>Industr. No FGR</td>
<td>NG, Coal</td>
<td></td>
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<tr>
<td>Oxy-coal UK UK</td>
<td>UK</td>
<td>40</td>
<td>2008</td>
<td>Pilot PC</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vattenfall Germany</td>
<td>Germany</td>
<td>30</td>
<td>2008</td>
<td>Pilot PC</td>
<td>Lignite (Bit.)</td>
<td>With CCS</td>
</tr>
<tr>
<td>Total, Lacq France</td>
<td>France</td>
<td>30</td>
<td>2009</td>
<td>Industrial</td>
<td>Nat gas</td>
<td>With CCS</td>
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<tr>
<td>Pearl Plant USA</td>
<td>USA</td>
<td>66</td>
<td>2009</td>
<td>22 MWe PC</td>
<td>Bit</td>
<td>Side stream</td>
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<tr>
<td>Callide Australia</td>
<td>Australia</td>
<td>90</td>
<td>2010</td>
<td>30 MWe PC</td>
<td>Bit.</td>
<td>With CCS</td>
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<tr>
<td>Ciuden - PC Spain</td>
<td>Spain</td>
<td>20</td>
<td>2010</td>
<td>Pilot PC</td>
<td>Anthra.(Pet ck)</td>
<td>?</td>
</tr>
<tr>
<td>Ciuden - CFB Spain</td>
<td>Spain</td>
<td>30</td>
<td>2010</td>
<td>Pilot CFB</td>
<td>Anthra.(Pet ck)</td>
<td>?</td>
</tr>
<tr>
<td>Jamestown USA</td>
<td>USA</td>
<td>150</td>
<td>2013</td>
<td>50 MWe CFB</td>
<td>Bit.</td>
<td>With CCS</td>
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<tr>
<td>Vattenfall (Janschwalde) Germany</td>
<td>~1000</td>
<td>2015</td>
<td>~250 MWe PC</td>
<td>Lignite (Bit.)</td>
<td>With CCS</td>
<td></td>
</tr>
<tr>
<td>Youngdong Korea</td>
<td>Korea</td>
<td>~400</td>
<td>2016?</td>
<td>~100 MWe PC?</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Endessa Spain</td>
<td>Spain</td>
<td>~1500</td>
<td>2015?</td>
<td>~500 MWe CFB?</td>
<td>?</td>
<td>With CCS</td>
</tr>
</tbody>
</table>
ANL - EERC Study
World's 1st Oxy-Coal Industrial Pilot Scale Study
Tower Furnace (~ 3MWth)
Challenges in the Development of Oxyfuel Combustion for Power Plant with CO₂ Capture
Oxy-Coal Combustion Power Plant with CCS…
Where Can You Extract the Recycled Flue Gas (RFG)
(For some practical application using low S coal)
Oxygen Production

Acknowledged the slides from
Air Liquide
Air Products
Praxair
Current status of ASU

• The **only** available technology for oxygen production in large quantities is **cryogenic** separation today.

• Industrial gas companies could offer 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 (presented by Air Liquide) is totaling **40000 t/d**.
ASU Distillation Process

Double Column Cycle

LP COLUMN

N₂

O₂

Air

HP COLUMN

10 - 12%

Less kW

Side Column Cycle

N₂

O₂

Air

HP COLUMN

Liquid Vapor Equilibria Figure from F. Kerry (2007)
For 500 MWe (Net Output) – You will require ~10,500 t/d of oxygen!
Process Description: Oxygen supply

- Optimum oxygen purity suggested:
  - 95% - 97%
  - @ 95% O₂ you will have 2% N₂ and 3% Ar

- higher purity not worthwhile due to:
  - Excess O₂ requirement (19%)
  - Boiler air in leakage (1%)
  - ESP air in leakage (2%)
30 years of continuous Cryogenic ASU improvements

- Energy efficiency: x 1,75
- Productivity: x 2,8
Specific energy of separation in kWh per ton of oxygen

Impact on HHV efficiency: +1%
Impact on COE: -3.5%
What are the remaining issues...

- ~10,000 TPD of O₂ is required for a 500MWe (net) oxy-coal power plant with CCS.
  - This means that you will need 2 single trains of 5000 TPD ASU

- Remaining Issues
  - What could be the maximum capacity of oxygen production per train?
  - Operation flexibility (i.e. load following, etc…)
  - What will you do about the large volume of Nitrogen produced from this ASU?
Where are the other gaps in R&D for oxygen production?

- Non-conventional oxygen production
  - ITM – ions transport membrane (Air Products)
  - OTM – oxygen transport membrane (Praxair)
  - CAR – ceramics autothermal recovery (Linde / BOC)

- Chemical Looping Combustion
Challenges in the Boiler and Burner Development

Acknowledged the slides from
IVD Stuttgart

International Flame Research Foundation
Considerations in the Boiler Operation

Quality of the Recycled Flue Gas (RFG)

(a.) moisture content
(b.) Distribution between Primary and Secondary RFG
Factors affecting Recycle Ratio

- Critical factors affecting the optimum amount of recycled flue gas
  - Burner and boiler design (heat transfer and flame stability – oxygen distribution through burner)
  - Air ingress
  - Purity of oxygen from the ASU
  - Coal type
  - Level of moisture content in comburent
  - Comburent (oxidant) temperature
Mass balance calculation should have a firm basis!!!

- Primary control of the boiler is in the oxygen content of the flue gas (~3.5%vd)
- Requirements of the coal mill should define the quality of the primary RFG
- Defining how the burners should operate is a required step… We need to establish criteria that would result to good combustion. An important element to your process control.
- Criteria for heat transfer profile should define the quality of secondary RFG
  - Molar ratio of the oxidant
  - O₂ concentration in the secondary comburent

Data from ANL studies (1989)
## Optimum Recycle Ratio

Table 1: Some of the reported results for the optimum flue gas recycle ratio

<table>
<thead>
<tr>
<th>Burner Rating</th>
<th>Type of flue gas</th>
<th>Molar ratio $^1$ (CO$_2$ + H$_2$O)/O$_2$</th>
<th>$^2$ O$_2$ in Comburent</th>
<th>Recycle Ratio $^3$ RFG / (RFG + PFG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANL (EERC)</td>
<td>dry recycle</td>
<td>2.66</td>
<td>~29%</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>wet recycle</td>
<td>3.25</td>
<td>~31%</td>
<td>~0.68</td>
</tr>
<tr>
<td>IFRF</td>
<td>wet recycle</td>
<td>~2.20</td>
<td>~48%</td>
<td>0.58</td>
</tr>
<tr>
<td>IHI</td>
<td>wet recycle</td>
<td>-</td>
<td>32% - 36%</td>
<td>-</td>
</tr>
<tr>
<td>CANMET</td>
<td>wet recycle</td>
<td>-</td>
<td>35%</td>
<td>-</td>
</tr>
</tbody>
</table>

$^1$ Molar ratio of the comburent (oxidant)  
$^2$ %oxygen through the burner throat  
$^3$ RFG and PFG are the mass flow rate of the recycle flue gas and the product flue gas respectively
Impact of the moisture content of the Recycled Flue Gas

Data from ANL studies (1987)
Considerations in the Boiler Operation

O$_2$ Purity and Air Ingress

(a.) Why not 99+\% O$_2$ Purity
(b.) Air Ingress… A Challenge for the Operator
Issue of Air Ingress (Air In-leakage)

Air Ingress in the boiler is a fact of life!!!

1\textsuperscript{st} Large Scale Demonstration of Oxy-Coal Combustion (35MWth)
– What Are the Lesson Learned...
Problem with Air Ingress

1st Large Scale Oxy-Coal Combustion Burner Test Experience - International Combustion Ltd.

- 30 MWth Low NOx burner
- Because of Air Ingress the desired CO$_2$ composition (only ~ 28% dry basis).
- 1% of air ingress ~ 4% decrease in CO$_2$ composition.
- the combustion trial gained significant experience in burner start up
NOx Emissions

- We have quite a good confidence in knowing the trend of these emissions
NOx Emissions
(Results from ANL-EERC and IFRF)
Results from IFRF study (APG4)
SO$_2$ Emissions

- Highly dependent on how sulphur is captured in ash...
SO₂ Emissions  
(Results from ANL-EERC and IFRF)
Sulphur in ash

http://www.ieagreen.org.uk
My (Question) Conundrum!!!

- Reduction of SO$_2$ under oxy-coal combustion conditions - Could this observations due to 2 competing phenomena in the furnace and in the convective section???
  - High temperature sulfation of the ash (as proposed by Okazaki et. al.) - which could probably be in agreement base on the data of IFRF (APG2 Trials).
  - Sulfur capture in ash at convective section enhanced by higher SO$_3$ formation, higher deposition rate and lower carbon in ash.
Drastic Enhancement of In-furnace Desulfurization Efficiency

Oxygen-fuel ratio = 1.2
One pass residence time = 8 s
Ca/S = 5
CaCO₃ (10 μm)

η at S = 1 wt %
six times higher

In-furnace desulfurization at high temperature

Air: impossible

O₂/CO₂: can be realized

η in O₂/CO₂ ➔ about four times higher
high in a wide temperature range

Effect of temperature on system desulfurization efficiency

School of Engineering
Tokyo Institute of Technology

Liu & Okazaki, ENERGY & FUEL, 2001
Mechanism of In-furnace Desulfurization

What is in-furnace desulfurization?

A very economical method of $\text{SO}_2$ removal through sorbent ($\text{CaCO}_3$) injection into the furnace

<LIu & Okazaki, ENERGY & FUEL, 2001>

Desulfurization reaction:

$$\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2$$
$$\text{CaO} + \text{SO}_2 + \frac{1}{2}\text{O}_2 \rightarrow \text{CaSO}_4$$

CaSO$_4$ decomposition:

$$\text{CaSO}_4 \rightarrow \text{CaO} + \text{SO}_2 + \frac{1}{2}\text{O}_2$$

The cause of decrease in desulfurization efficiency at high temperature

School of Engineering

Tokyo Institute of Technology
Oxygen-fuel ratio = 1.2
One pass residence time = 8 s
$Ca/S = 5$
$CaCO_3 (10 \mu m)$

Contributions of different factors to the increase in system desulfurization efficiency
Results from IFRF study (APG2)
Results from IFRF study (APG2)
Issue of $\text{SO}_3$

- The confirmation of the ANL results as presented by IVD Stuttgart study

- Nonetheless, there are still a lot of confirmation to be done!!!
Oxy-Combustion: KEY ISSUES

- SO₃ issue is a big missing link! (3 years ago)
- ANL study (1985) have indicated that SO₃ formation is 3 to 5 times greater as compared to conventional air – firing mode
- We need to know more about the potential operational issue.

From Chemical Engineering Progress (Vol. 70)
Impact of $\text{SO}_3$

Data from ANL Studies (1980s) - Black Thunder Coal
Measured SO$_3$ concentrations for Lausitz coal at AIR and OXYFUEL combustion conditions

<table>
<thead>
<tr>
<th></th>
<th>SO$_2$ measured</th>
<th>SO$_3$ measured</th>
</tr>
</thead>
<tbody>
<tr>
<td>ppm</td>
<td>ppm</td>
<td></td>
</tr>
<tr>
<td>AIR (*)</td>
<td>733</td>
<td>0.08 (0.06 – 0.11)*</td>
</tr>
<tr>
<td>OXYFUEL (◊)</td>
<td>1758</td>
<td>8.5 (3.6 – 12.1)*</td>
</tr>
</tbody>
</table>
My Background Analysis...

- SO$_2$ to SO$_3$ conversion will most likely to occur at the convective section…

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**Fig. 3.** Conversion of SO$_2$ to SO$_3$ in the presence of fly ash as a function of temperature.

Marrier and Dibbs (1974) *Thermochimica Act* (Vol. 8)
SO\textsubscript{2} captured along the convective part (down to 450°C) by different inlet concentrations

Oxy-fuel 27 % O\textsubscript{2}
SO₃ formation is increased in the presence of iron oxide in the ash.

Fig. 4. Conversion of SO₂ to SO₃ at 700°C as a function of the Fe₂O₃ content of fly ash.

Marrier and Dibbs (1974) Thermochemica Act (Vol. 8)
IHI – Callide Project Results (SO₂ Emissions)

IFRF (APG1 Trials) – Gottelborg coal

ANL-EERC Trials – Blk. Thunder coal
Would the capture of SO$_2$ / SO$_3$ in the ash enhanced by lower carbon in ash?

Marrier and Dibbs (1974) *Thermochimica Act* (Vol. 8)

E.ON UK Results at 26%O$_2$
Ash Related Issue

Black Thunder Coal

Data from ANL-EERC Trials
Ash Related Issue

Data from the trials taken by:
MBEL, Air Products, Ulster University and Naples University (1995)
Capture of sulphur in ash at the furnace section is primarily due to the high temperature direct sulphation mechanism as suggested by Okazaki et. al. (2001) as shown in their experimental results. This is pretty much in agreement to the in-flame SO$_2$ measurements done by IFRF during their APG2 trials.

- Okazaki et. al. suggested that this is due to promotion of capture of sulphur by CaO species and the inhibition of the decomposition of CaSO$_4$.
- This mechanism is further supported from the results of IVD Stuttgart (Maier et. al.) and Imperial College (Wrigley et. al.) indicating the occurrence of both carbonation and sulphation in the ash collected from oxy-coal combustion trials. This could indicate that equilibrium reactions promoting the formation of CaCO$_3$ and CaSO$_4$ are probably favoured (or highly enhanced) under CO$_2$ rich environment.
- These results established the feasibility of using in-furnace SO$_2$ reduction by using Ca(OH)$_2$ or CaO injection.
• Additional sulphur capture in ash could also be promoted by increased formation of SO$_3$.
  • It should be recognised that both results from ANL-EERC and IVD Stuttgart confirms that SO$_3$ formation is higher (about 4-5 times – in terms of mass SO$_3$ emissions per unit energy input) as compared to air fired case. However, it is not yet clear if level of recycled SO$_2$ has it impact to the level of SO$_3$ formation.
  • Capture of sulphur by this mechanism would occur along the flue gas path (during the convective section) as shown in the results by IVD-Stuttgart.
    • Furthermore, IVD-Stuttgart results indicated that the higher the level of SO$_2$ are recycled, the capture efficiency of sulphur in ash is more efficient.
    • Nonetheless, it should be noted that that this observation in sulphur capture efficiency is coal dependent.
Summary SO\textsubscript{2}/SO\textsubscript{3} and Sulphur in Ash – (3)

- Results from Marrier and Dibbs (1974) further support the observations made by IVD Stuttgart:
  - maximum conversion of SO\textsubscript{2} to SO\textsubscript{3} would occur around 700-800°C.
  - Capture of sulphur in ash could be dependent on the concentration of CaO and MgO in the ash. (This could probably be one of the reasons why capture efficiency of sulphur becomes coal dependent)
  - Iron oxides could enhanced the formation of SO\textsubscript{3} therefore promoting the capture of sulphur in the ash at the convective section. (This could probably be one of the reasons why capture efficiency of sulphur becomes coal dependent).
  - Carbon in ash could diminish the efficiency in the capture of sulphur in ash. This is supported by various studies indicating a lower carbon in ash during oxy-coal combustion trials (IHI, IFRF, ANL-EERC) showed a lower SO\textsubscript{2} emissions (i.e. higher degree of sulphur capture in ash). A higher carbon in ash by E.ON UK experimental results indicated a nearly similar SO\textsubscript{2} emissions to the air fired case.
- Higher ash deposition rate under the wet RFG trials could also promote higher sulphur capture in the convective section. **This should be further validated!**
Oxy-Coal Combustion Technology Development
(CO$_2$ Purification and Compression)
Purification of Oxyfuel-Derived CO2 for Sequestration or EOR

- CO₂ produced from oxyfuel requires purification
  - Cooling to remove water
  - Inert removal
  - Compression

- Current design has limitations
  - SOx/NOx removal
  - Oxygen removal
  - Recovery limited by phase separation

- Necessary to define CO₂ quality requirement!!!
25% mol CO₂
75% inerts (~ 15% O₂)

96% mol CO₂
4% inerts (~ 0.95% O₂)

76% mol CO₂
24% inerts (~ 5 - 6% O₂)
**CO₂ Purity and Recovery**

- -55°C is as cold as we can make the phase separation

- CO₂ purity depends on pressure
  - At 30 bar and -55°C, CO₂ purity is 95%
  - Higher pressure gives lower purity CO₂

- CO₂ recovery depends on pressure
  - Lower pressure gives lower CO₂ recovery
  - At 15 bar and -55°C, CO₂ recovery is 75%
  - At 30 bar and -55°C, CO₂ recovery is 90%

- CO₂ recovery depends on feed composition
  - Increases from zero at 25mol% to 90% at 75mol%
  - Reducing air ingress increases CO₂ capture rate
**CO₂ Purity Issues**

<table>
<thead>
<tr>
<th></th>
<th>Basic Design Case</th>
<th>EOR Case</th>
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<tbody>
<tr>
<td>H₂O</td>
<td>&lt; 500 ppm</td>
<td>&lt; 50 ppm</td>
</tr>
<tr>
<td>CO₂</td>
<td>&gt; 90% mol</td>
<td>&gt; 90% mol</td>
</tr>
<tr>
<td>SO₂</td>
<td>From H&amp;MB</td>
<td>&lt; 50 ppm</td>
</tr>
<tr>
<td>NO</td>
<td>From H&amp;MB</td>
<td>From H&amp;MB</td>
</tr>
<tr>
<td>O₂</td>
<td>&lt; 4% mol</td>
<td>100 ppm</td>
</tr>
<tr>
<td>Ar + N₂ + O₂</td>
<td>&lt; 4% mol</td>
<td>&lt; 4% mol</td>
</tr>
</tbody>
</table>
25% mol CO₂
75% inert
(~ 19% O₂)

72% mol CO₂
28% inert
(~ 5 - 6% O₂)

98% mol CO₂
2% inert
(~ 0.6% O₂)
25% mol CO₂
75% inerts
(~ 15% O₂)

72% mol CO₂
28% inerts
(~ 5 - 6% O₂)

99.95% mol CO₂
0.05% inerts
(~ .01% O₂)
Purity, Recovery and Power

- Power includes ASU and CO₂ system power

<table>
<thead>
<tr>
<th>Description</th>
<th>CO₂ Purity</th>
<th>Oxygen Content</th>
<th>CO₂ Pressure</th>
<th>CO₂ Recovery</th>
<th>Relative Specific Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standard Cycle</td>
<td>95.90 mol%</td>
<td>0.91 mol%</td>
<td>110 bar</td>
<td>89.0%</td>
<td>1.00</td>
</tr>
<tr>
<td>High Purity Option 2</td>
<td>99.98 mol%</td>
<td>100.00 ppm</td>
<td>110 bar</td>
<td>87.7%</td>
<td>0.99</td>
</tr>
<tr>
<td>30 bar liquid CO₂</td>
<td>99.98 mol%</td>
<td>100.00 ppm</td>
<td>30 bar</td>
<td>87.7%</td>
<td>0.98</td>
</tr>
<tr>
<td>7 bar liquid CO₂</td>
<td>100.00 mol%</td>
<td>5.01 ppm</td>
<td>7 bar</td>
<td>87.7%</td>
<td>1.02</td>
</tr>
</tbody>
</table>
25%mol CO₂
75% inerts
(~ 15% O₂)

72%mol CO₂
28% inerts
(~ 5 - 6% O₂)

99.999%mol CO₂
0.001% inerts
(~ .0005% O₂)
Air Product’s “Sour Compression Process”
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:
  - $\text{NO} + \frac{1}{2} \text{O}_2 = \text{NO}_2$ (1) Slow
  - $2 \text{NO}_2 = \text{N}_2\text{O}_4$ (2) Fast
  - $2 \text{NO}_2 + \text{H}_2\text{O} = \text{HNO}_2 + \text{HNO}_3$ (3) Slow
  - $3 \text{HNO}_2 = \text{HNO}_3 + 2 \text{NO} + \text{H}_2\text{O}$ (4) Fast
  - $\text{NO}_2 + \text{SO}_2 = \text{NO} + \text{SO}_3$ (5) Fast
  - $\text{SO}_3 + \text{H}_2\text{O} = \text{H}_2\text{SO}_4$ (6) Fast

- Rate increases with Pressure to the 3$^{rd}$ 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.


**CO₂ Compression and Purification System – Removal of SO₂, NOx and Hg**

- **SO₂ removal:** 100%
- **NOx removal:** 90-99%

**Process Details:**

- **1.02 bar 30°C**
  - 67% CO₂
  - 8% H₂O
  - 25% Inerts
  - SOx NOx
- **30 bar to Driers**
  - Saturated 30°C
  - 76% CO₂
  - 24% Inerts

**Diagram Highlights:**

- Condensate
- BFW
- 15 bar
- Dilute H₂SO₄
- HNO₃
- Hg
- Water
- 30 bar
- CW
- Dilute HNO₃
- CW
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 NO₂ and then NO₂ oxidises SO₂ to SO₃: The Lead Chamber Process

- Hg will also be removed, reacting with the nitric acid that is formed (To What Extent???)
CO₂ Processing (high purity case)
Air Product’s
“Use of Membrane for further recovery of oxygen and CO₂”
Use of Membrane to recover CO₂ and O₂ at the vent

Vent:
7% CO₂
93% inerts
(~10% O₂)

Product
96% CO₂
4% inerts
(~0.75% O₂)
Issues involving CO₂ purification process

• We need to establish what is appropriate and acceptable level of impurities in our CO₂ based on aspects of:
  ○ Health, Safety and Environment considerations
    ▪ What are the regulations to be established without disadvantaging any capture technology (What is acceptable!!!)
  ○ Quality specifications defined by transportation/delivery of CO2 to the storage sites
    ▪ Also to consider the changes to the CO2 properties by the impurities and its possible reactions
  ○ Quality specifications defined by the storage CO2 for different storage options

• The quality of CO₂ (specific level of impurities) should be openly discussed!
Summary and Conclusions

(CO$_2$ Processing Unit)

• Depending on the requirement of the oxygen content, processes are now available to produce CO$_2$ purity from 95% - 99.999%.
  o It should be noted that higher the purity you reduce the CO$_2$ capture rate.
  o Higher purity means higher CAPEX and OPEX.

• Removal of SOx and NOx depends on the “lead chamber reaction” to occur. Removal could be achieve by compressions and direct contact acid water wash. This should be demonstrated in the large scale.
  o This presentation only present the Air Products process. Other option to consider is the installation of distillation column as proposed by Air Liquide.
Update to Vattenfall’s Schwarze Pumpe Pilot Plant Activities

Acknowledged the slides from Vattenfall AB
Schwarze Pumpe Power Plant
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
- Size of pilot plant chosen to facilitate a scale-up to a commercial-size burner as the next step
CO2 Tank and Furnace Delivery
Measurement ports in the furnace
The furnace in the making
ESP        Boiler steel structure     and equipment
Summary and Conclusions
Burner & Boiler Development

• Demonstration via large scale burner testing is essential to the development of oxy-combustion.

• Key areas of R&D should focus on:
  o Heat transfer and flame properties
  o Coal devolatilisatoin and char combustion
  o Slagging, fouling deposition characteristics
  o Emissions (sulphur chemistry, PM and Hg + trace metals)

• Development in CFD modelling is an essential tools to help design of future burners and boilers.
Failure Location

- Failure occurred at the base (6 o’clock) of the gas nozzle
- Evidence of de-lamination consistent with Liquid Metal Embrittlement (LME) caused by mercury in contact with aluminium
ASU & CPU

- 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 Processing Unit in the overall oxyfuel combustion plant are key to achieve high efficiency and low capital expenditure.
- Should also consider looking at novel oxygen production.
Concluding Remarks

• Several activities have been initiated worldwide in the development of Carbon Capture for Power Generation industry.
• There are two set of horse race among the three options for newly build and retrofit plant. There is no leader at the moment!
• We need large scale demonstration of the carbon capture technology to build the confidence necessary for a rapid deployment.
Footprint of Capture plant – DTI Project 407

- Oxyfuel and amine scrubbing have similar footprints

1 x ASC BT Oxyfuel Unit:
- 2 x ASU trains
- CO₂ Compression
- Maximum Height – 68m

1 x ASC BT Amine Unit:
- 2 x SO₂ removal towers (reduces SO₂ from 10ppm at FGD outlet to 1 ppm at CO₂ absorber inlet)
- 2 x Fans / Blowers
- 2 x CO₂ Absorber Towers (12.5m Dia x 45m Height)
- 1 x CO₂ Stripper Tower (10m Dia)

ASU & CO₂ Compression 24,500m²
Amine Scrubbing & CO₂ Compression 23,825m²