Oxy-Pulverised Coal Combustion Technology for Power Generation with CO_2 Capture

(Fundamental Engineering Principles in Understanding the Technology)

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Overview

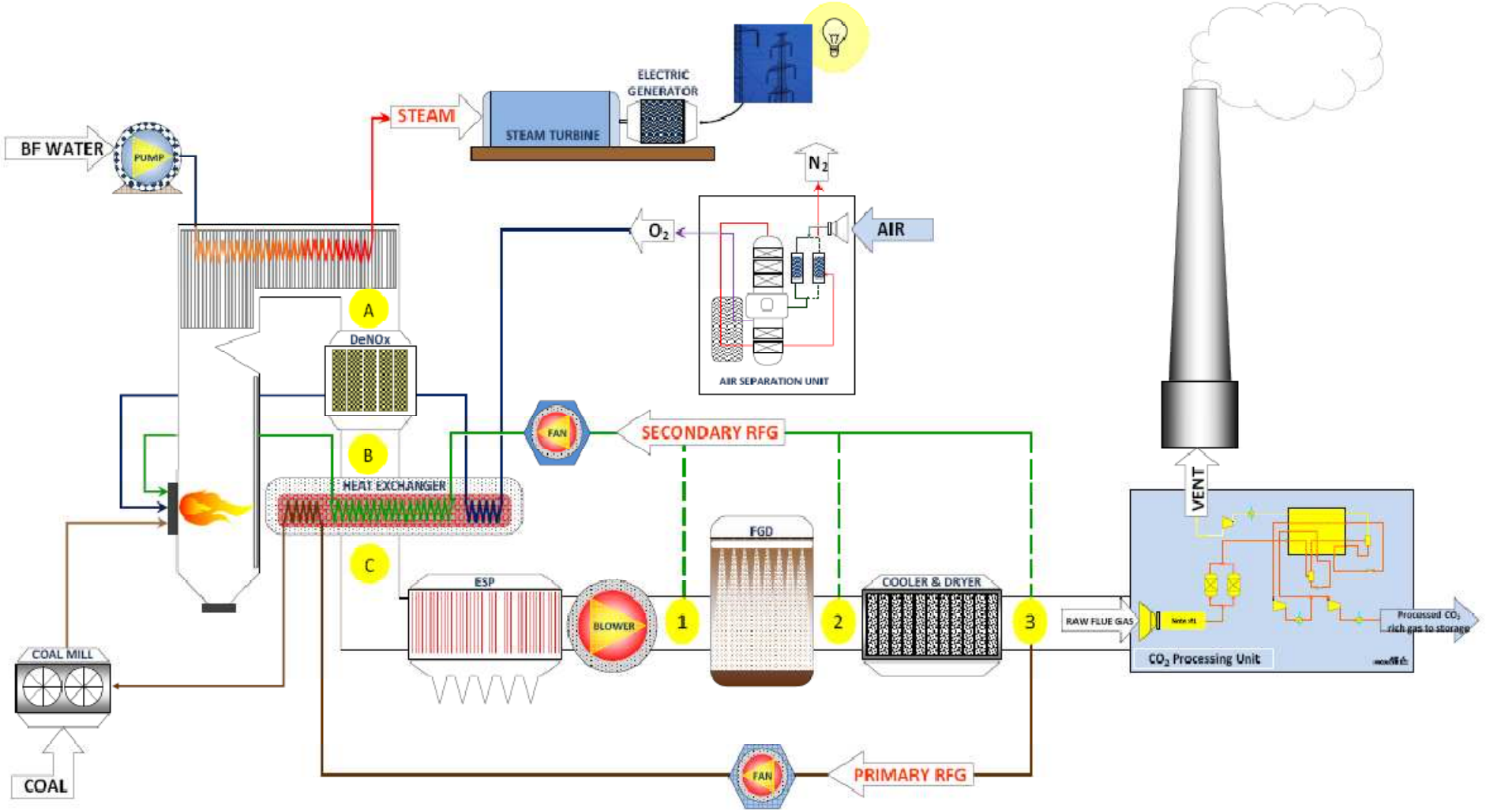
- ***Introduction – Oxyfuel Combustion***
- ***Overview to the Boiler and Burner Development***
  - Recycle of Flue Gas
- ***Overview to the Oxygen Production***
  - 2 column design – “Oxyton Cycle”
  - Double reboiler design
- ***Overview to the CO_2 Processing Unit***
  - NOx and SOx reaction during compression
  - Removal of Inerts
- ***Concluding Remarks***

Introduction

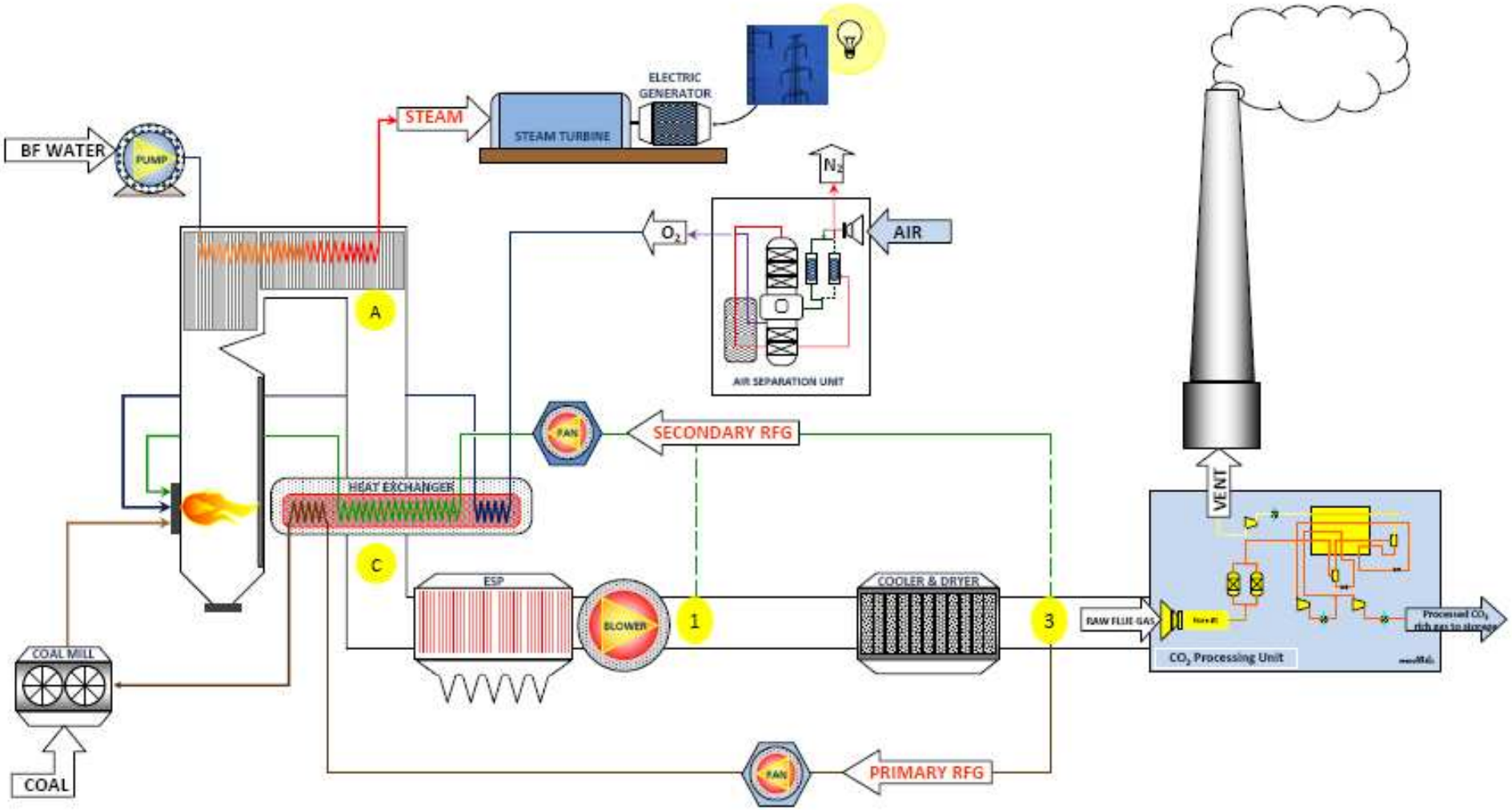
OXY-PULVERIZED COAL COMBUSTION FOR POWER GENERATION

Introduction

Oxyfuel Combustion for Coal Fired Power Plant with CO_2 Capture



Where Can You Extract the Recycled Flue Gas (RFG)
(For some practical application using low S coal)



Overview to Boiler and Burner Development

IMPACT OF RECYCLE FLUE GAS TO THE BOILER OPERATION

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

7

Mass balance calculation should have a firm basis!!!

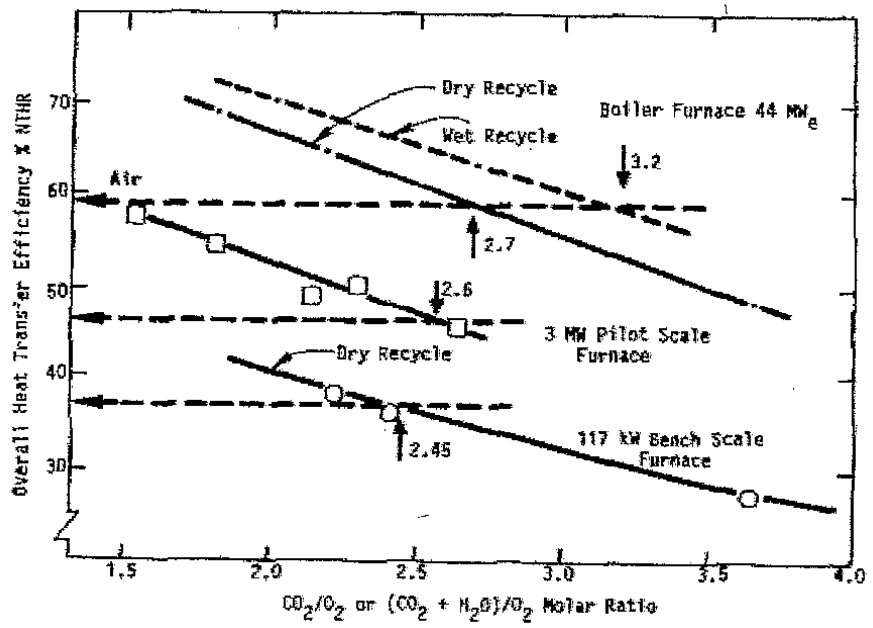
Primary control of the boiler is in the oxygen content of the flue gas (~3.5%vd)

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
- O_2 concentration in the secondary comburent



Data from ANL studies (1989)

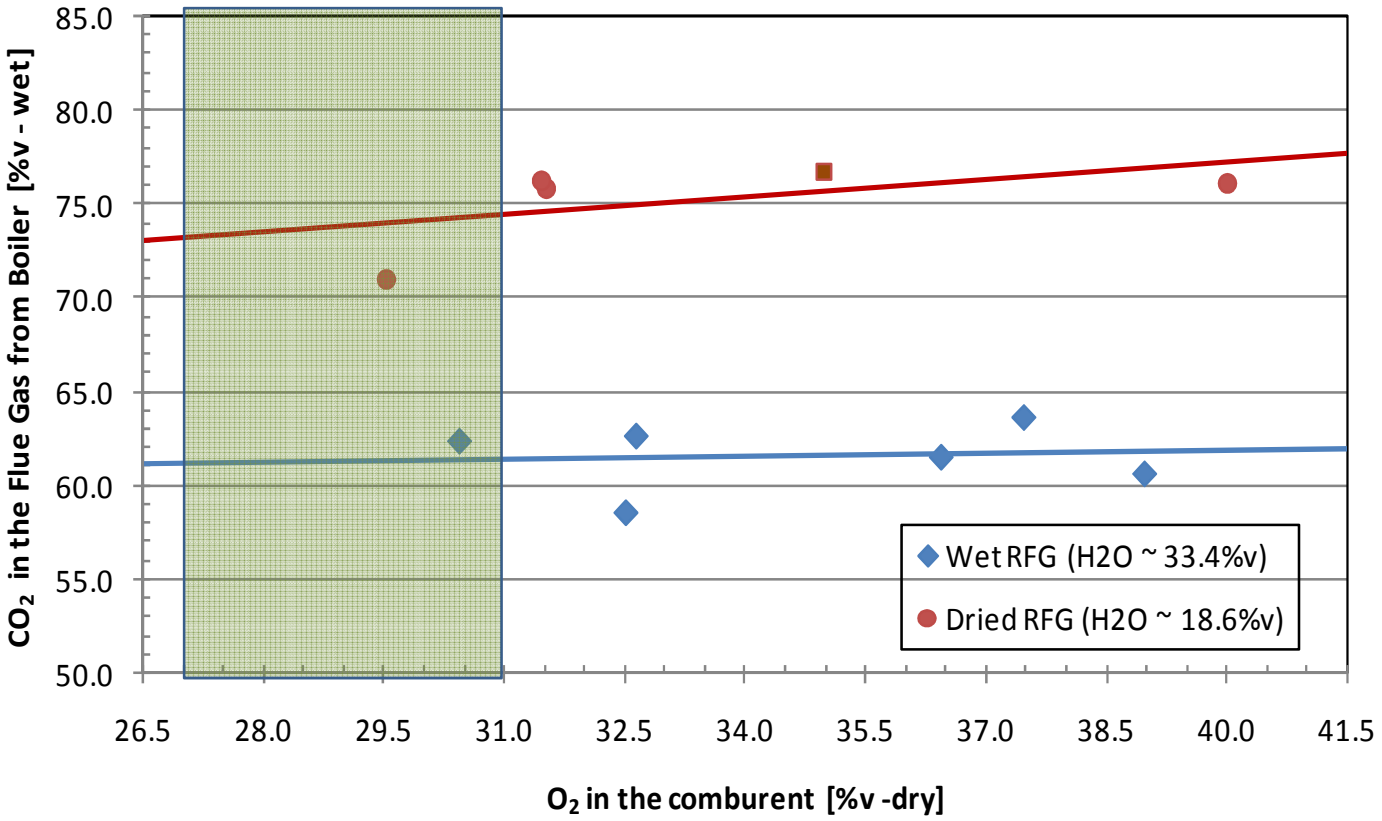
Optimum Recycle Ratio

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

	Burner Rating	Type of flue gas	Molar ratio[1] $(CO_2 + H_2O)/O_2$	% O_2 in Comburent[2]	Recycle Ratio[3] RFG / (RFG + PFG)
ANL (EERC)	3 MW_{th}	dry recycle	2.66	~29%	-
		wet recycle	3.25	~31%	~0.68
IFRF	2.5MW_{th}	wet recycle	~2.20	~48%	0.58
IHI	1.2MW_{th}	wet recycle	-	32% - 36%	-
CANMET	300 kW_{th}	wet recycle	-	35%	-

[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)

Flame Description – Impact of Recycle Ratio
(Courtesy of IFRF)

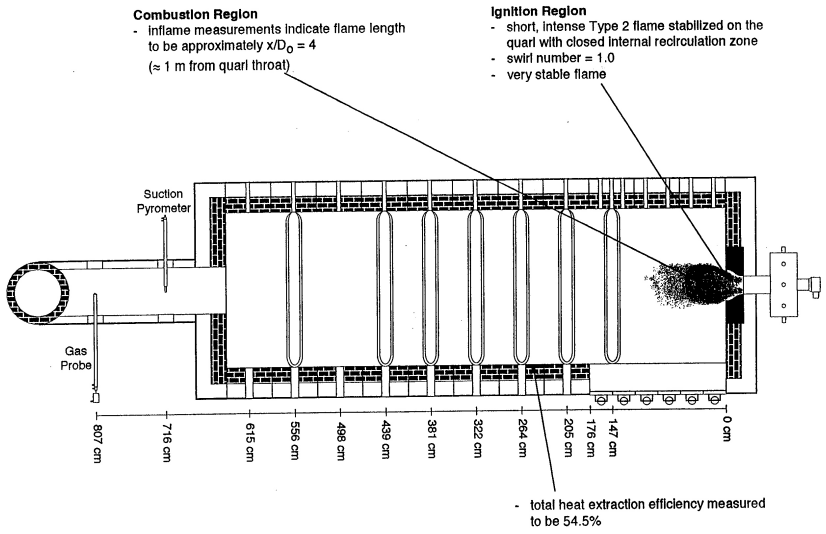


Figure 3(a): normal air-fired operation

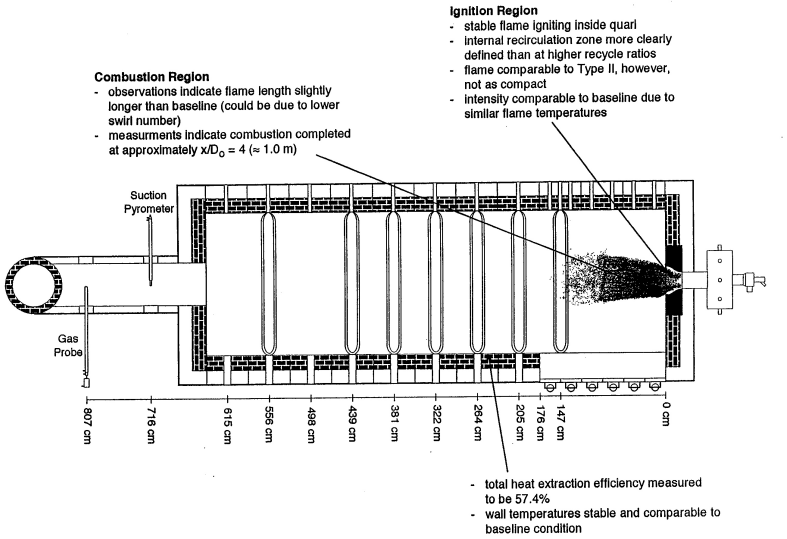


Figure 3(b): O_2-RFG flame with recycle ratio = 0.58

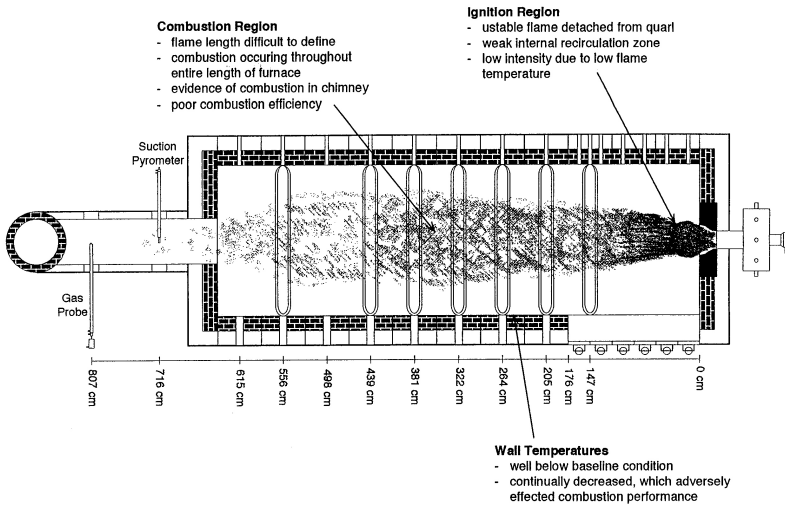


Figure 3(c): O_2-RFG flame with recycle ratio = 0.76

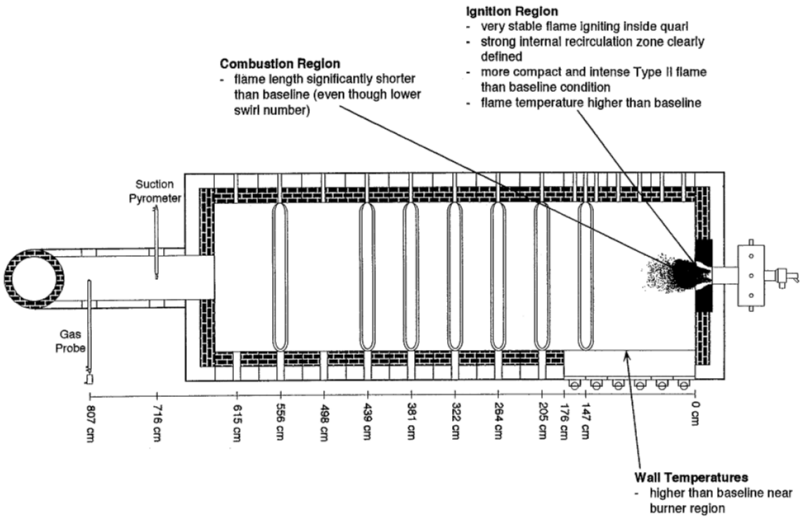
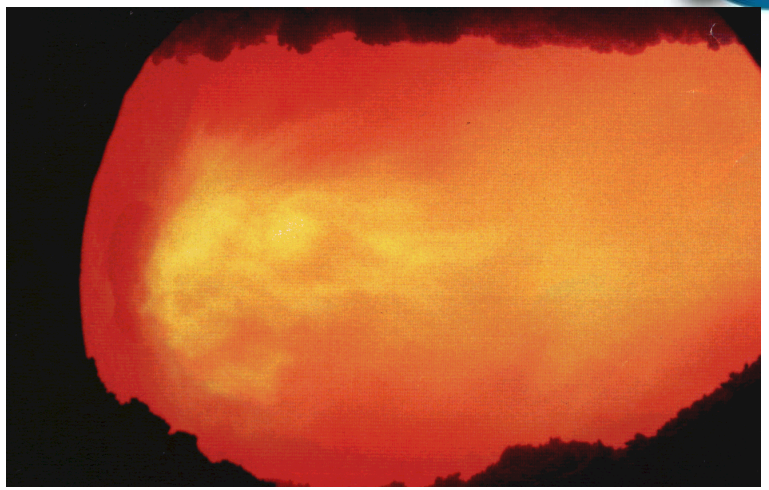
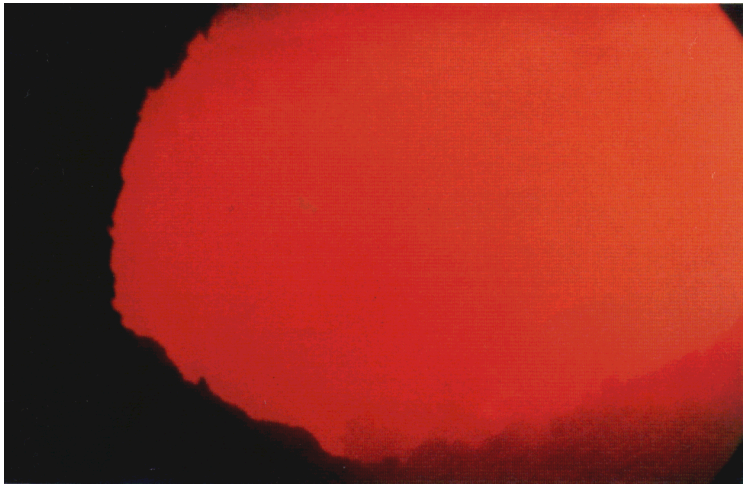


Figure 3(d): O_2-RFG flame with recycle ratio = 0.52

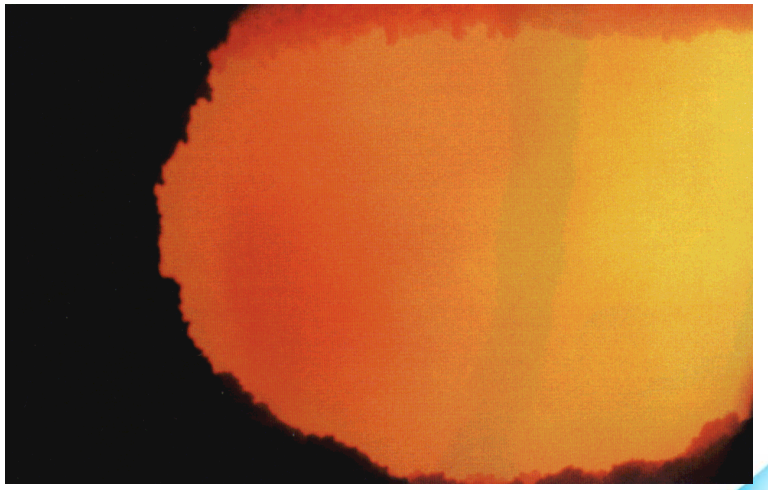
Coal Flame Photos: Air Fired vs Oxy-Fired (Courtesy of IHI)



Air mode（O_2：21%）



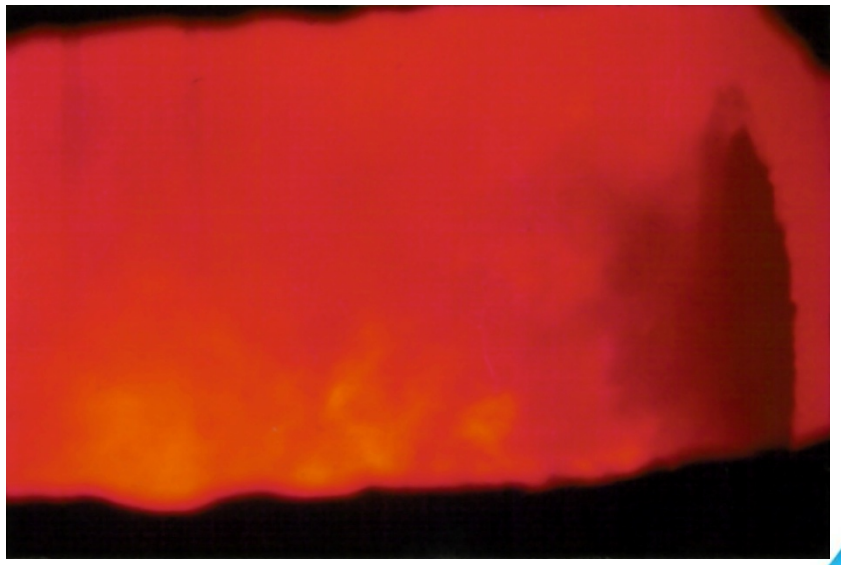
Oxy mode（O_2：21%）



Oxy mode（O_2：30%）

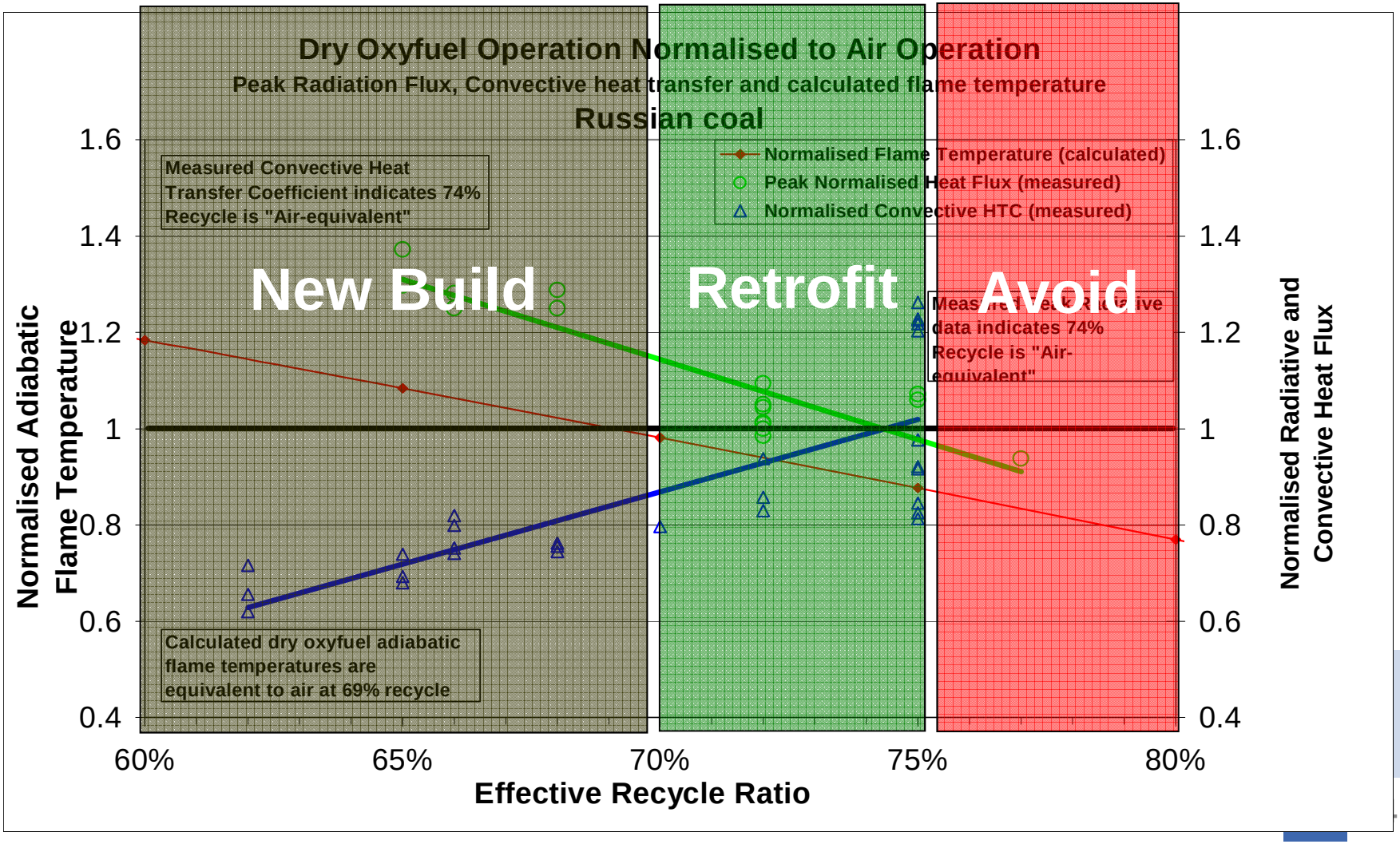
Coal Flame Photos: Impact of Recycled Flue Gas (Courtesy of IFRF)

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



Recycle Ratio = 0.76

Normalised Convective & Radiative heat flux – Russian Coal - Dry Recycle



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

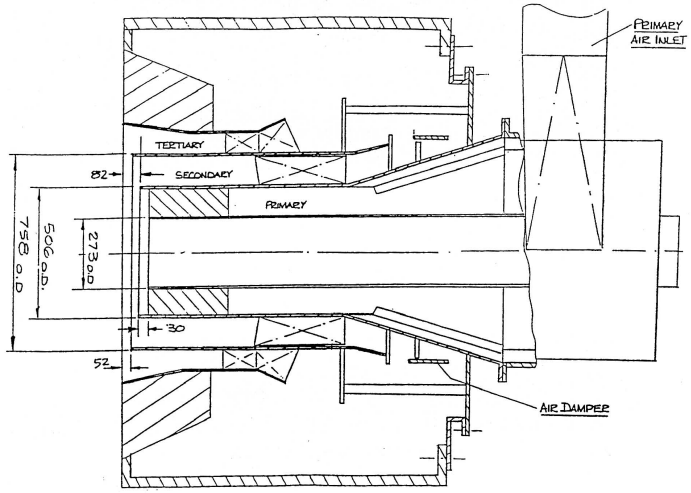
Issue of Air Ingress (Air In-leakage)

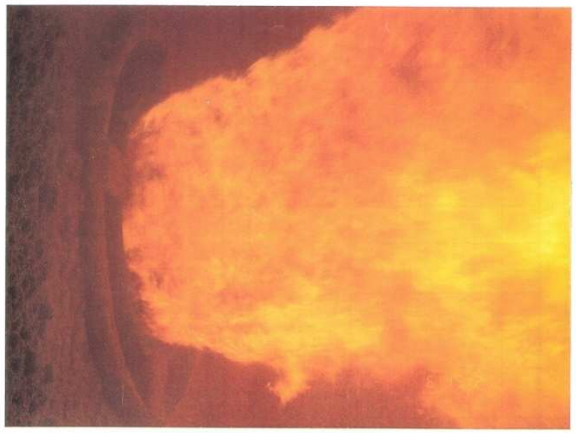
Air Ingress in the boiler is a fact of life!!!

1st Large Scale Demonstration of Oxy-Coal Combustion (35MWth) – What Are the Lesson Learned...

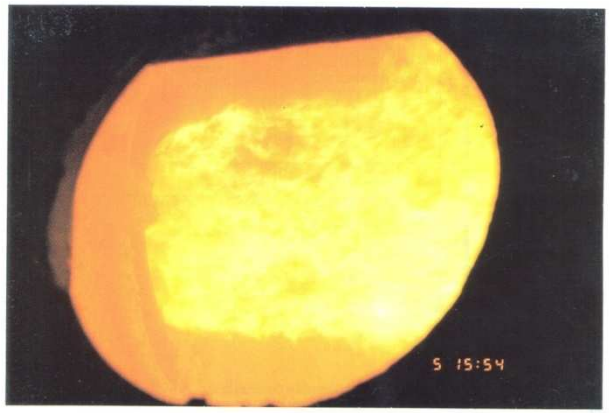
Problem with Air Ingress

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





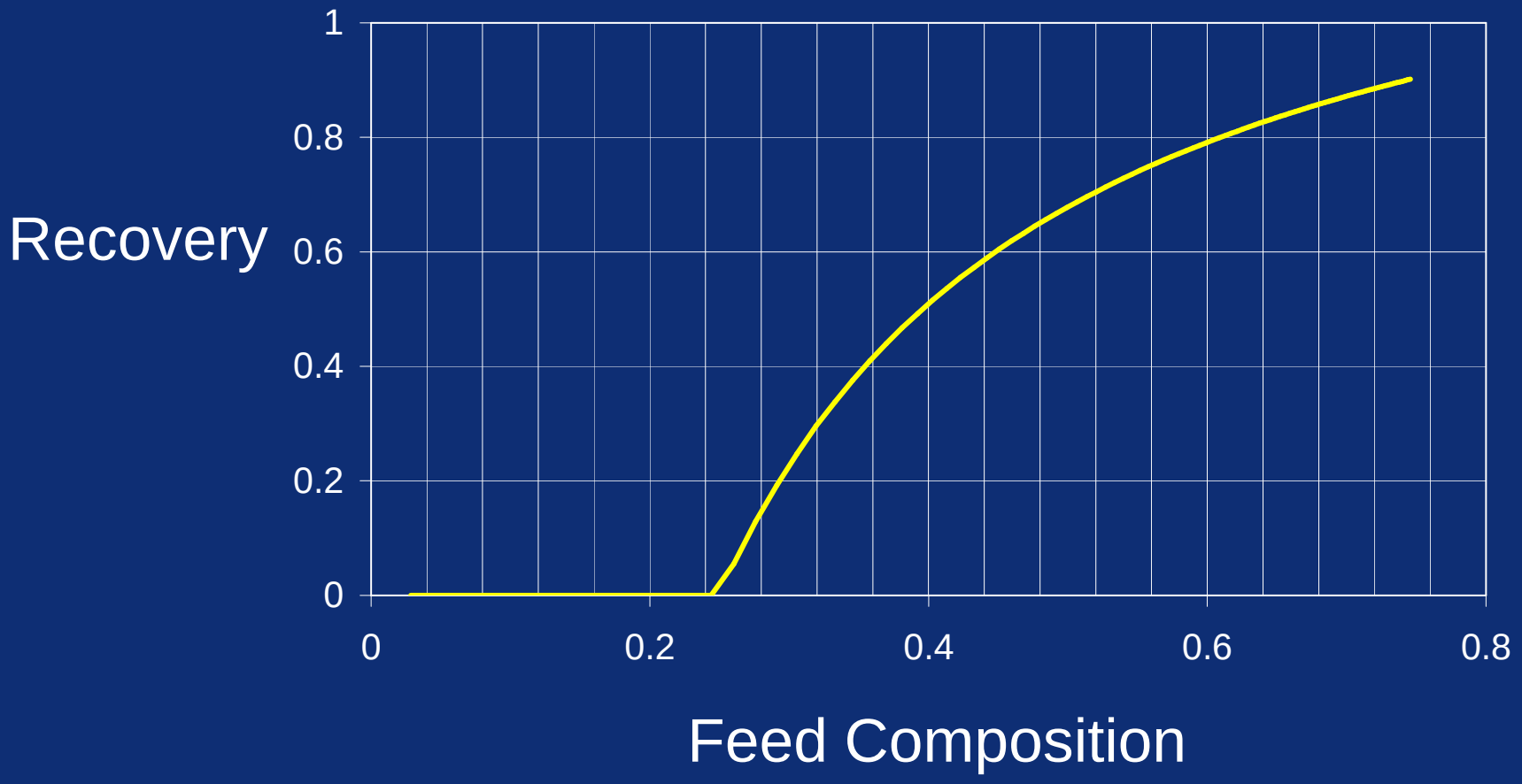
Test 1 - Conventional Air firing



Test 3 - O_2/RFG Firing

- ✓ 30 MWth Low NOx burner
- ✓ Because of Air Ingress the desired CO_2 composition (only ~ 28% dry basis).
- ✓ Air Ingress in boilers
  - ✓ approx. 3 % of flue gas flow for a new conventional power plant
  - ✓ up to 10 % over the years for power plants in use

CO_2 Recovery Depends On Feed Composition



At -55℃, 30 bar

AIR PRODUCTS

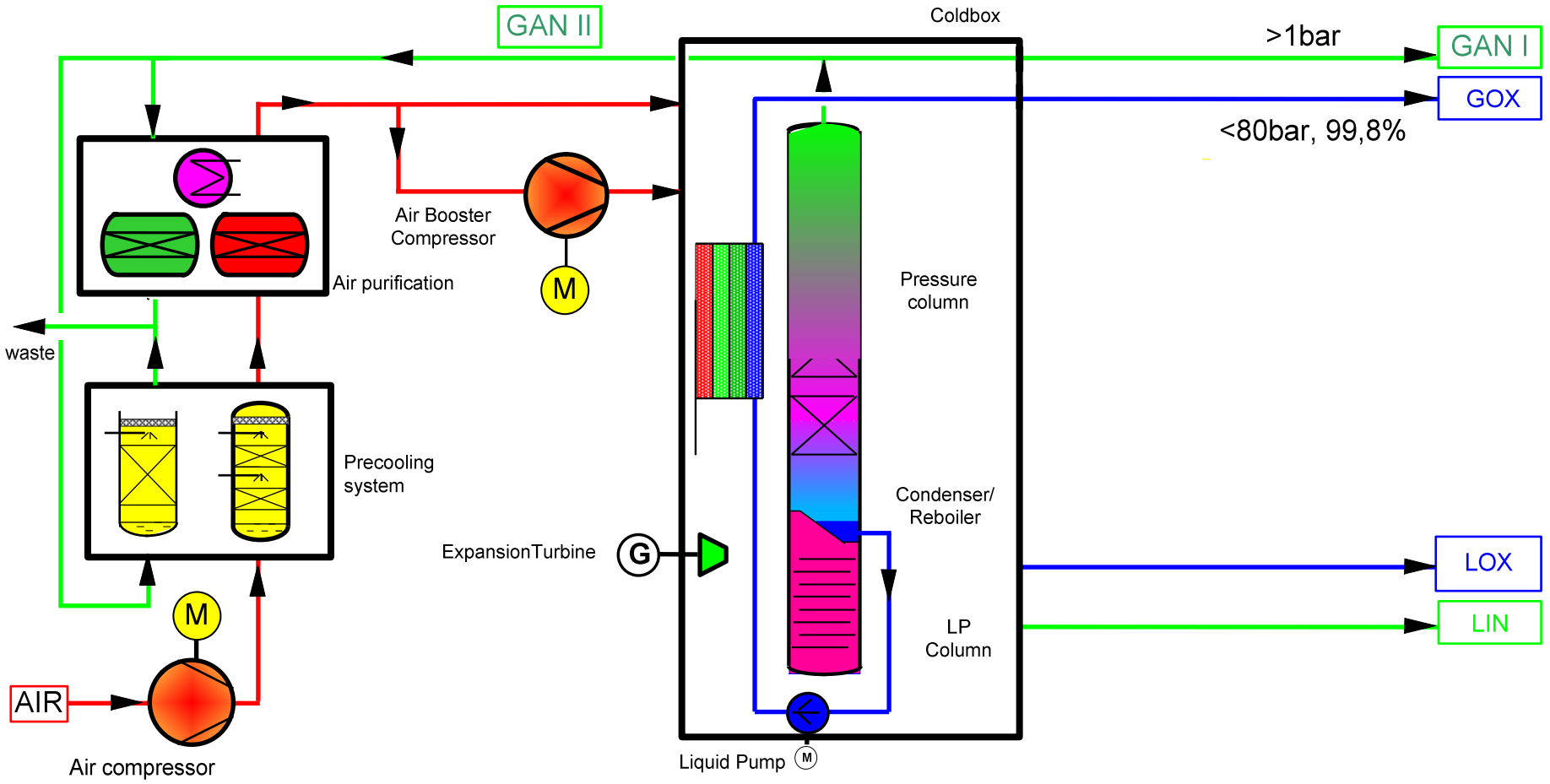
Oxygen Production

CHALLENGES TO THE DESIGN AND ENGINEERING OF THE AIR SEPARATION UNIT

Challenges to Oxygen Production

- *As of today, the only available technology for oxygen production in large quantities is **cryogenic air separation**.*
- *Advances and Development in ASU could result to 25% less energy consumption.*
  - These design would be based on either a 3 column design or dual reboiler design.
- *Challenges are:*
  - Cost of production of oxygen (energy consumption)
  - Utilisation of nitrogen within power plant.

Air Separation Plants
Simplified Air Separation Process



Air compression, -precooling and -purification	heat exchange, refrigeration, rectification and internal compression	product distribution

Cryogenic Air Separation – Capacity Increase

1902 :
5 kg/h
(0,1 ton/day)

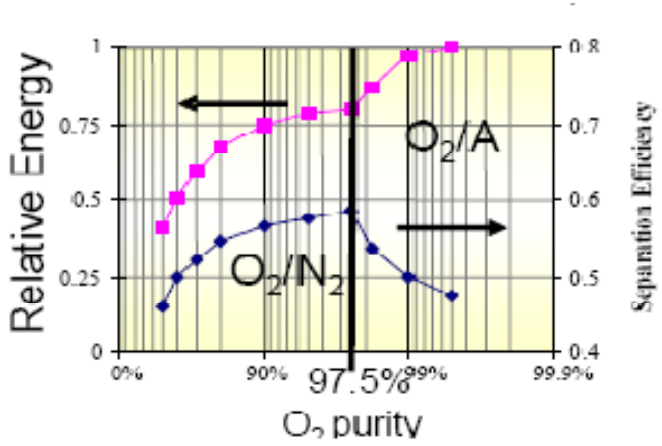
2006 :
1,250 Mio kg/h
(30.000 ton/day)

Air Separation Plants – Shell „Pearl“ GTL Project Qatar
30.000 tons/day Oxygen

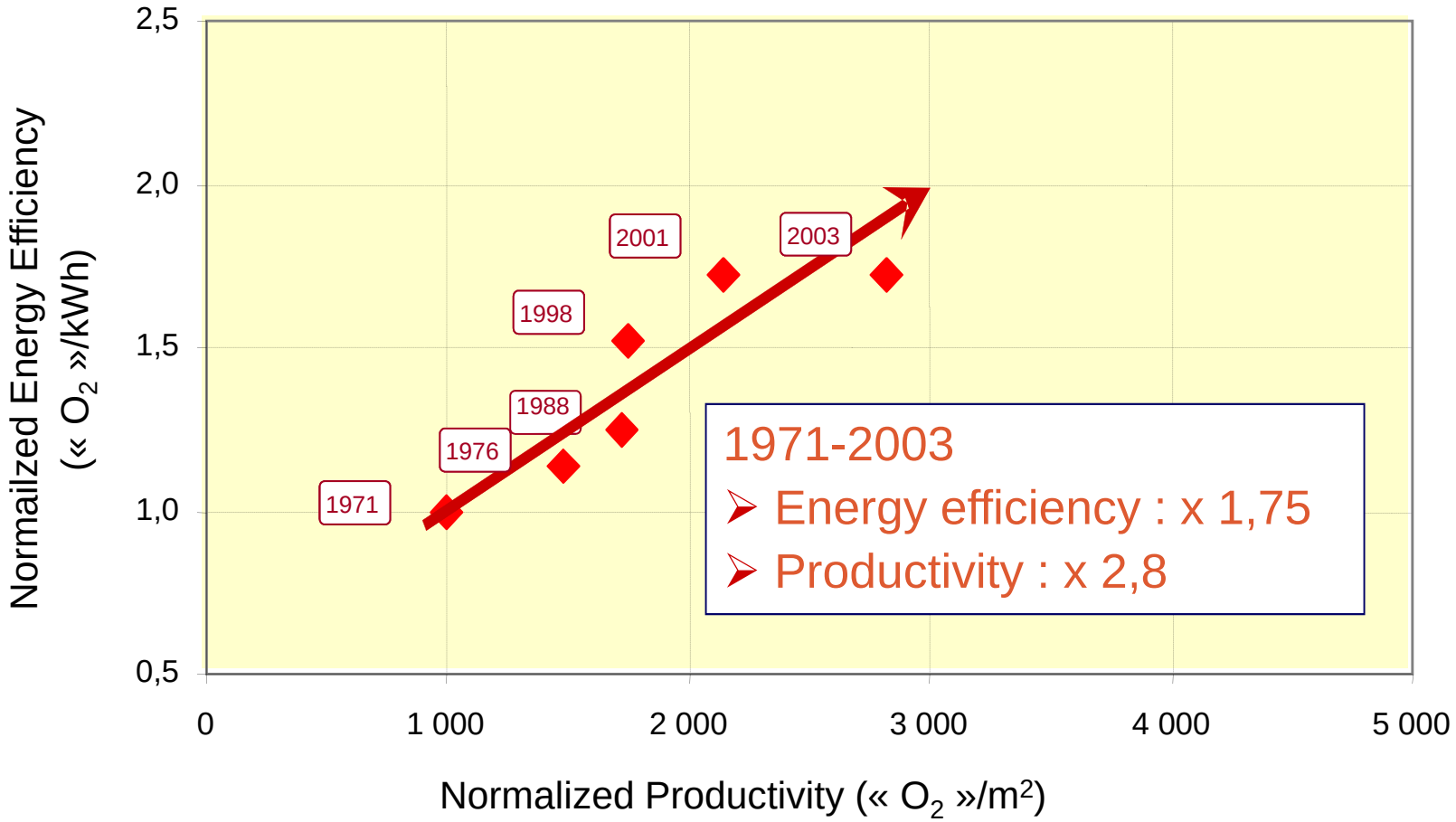
Process Description: Oxygen Supply

- ***Optimum oxygen purity suggested:***
  - 95% - 97%
  - @ 95% O_2 you will have 2% N_2 and 3% Ar

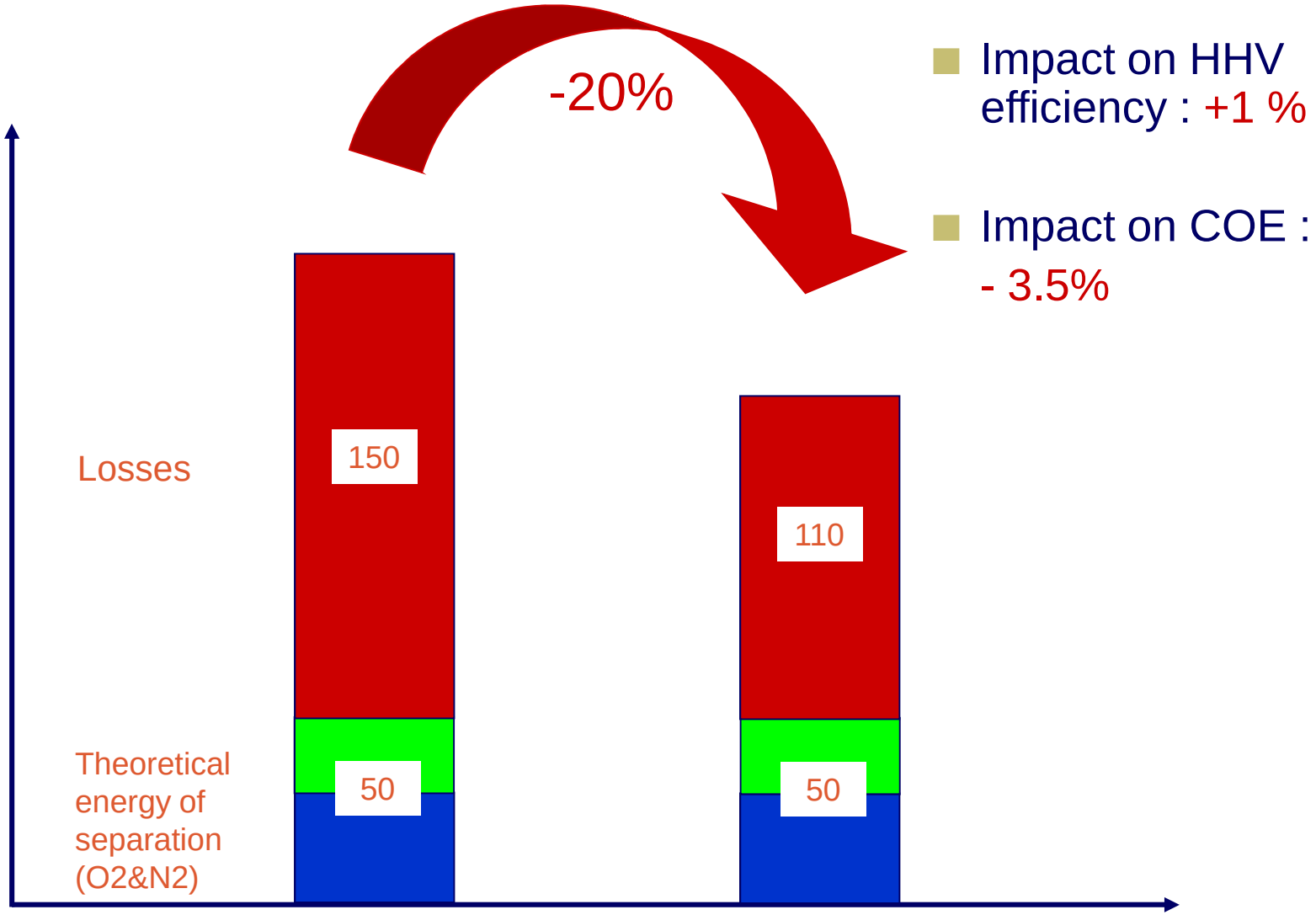
- ***higher purity not worthwhile due to:***
  - Excess O_2 requirement (19%)
  - Boiler air in leakage (1%)
  - ESP air in leakage (2%)



30 years of continuous Cryogenic ASU improvements



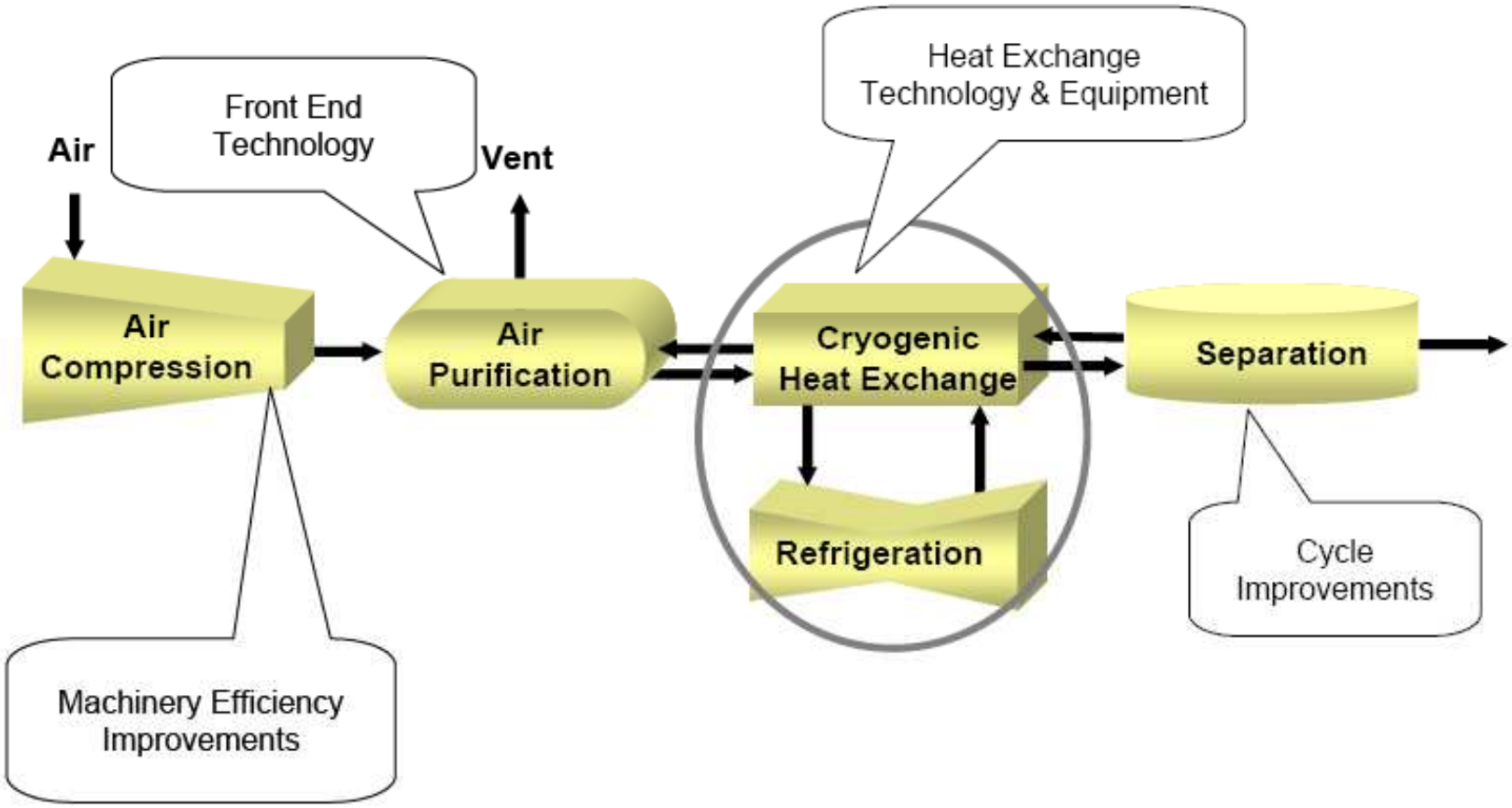
Specific energy of separation in kWh per ton of oxygen



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

Power Consumption Reduction Opportunities

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

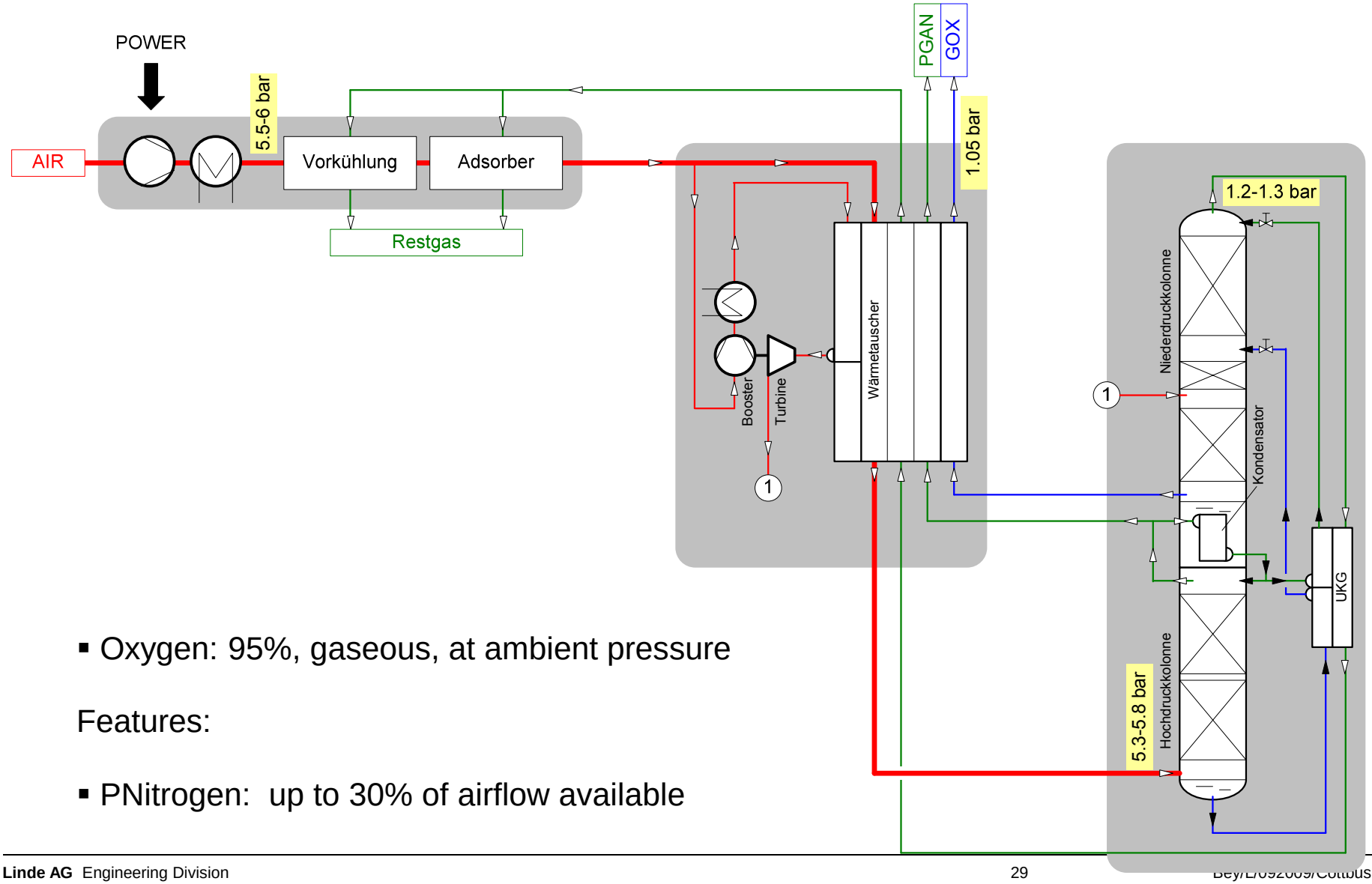


(*) 1 BAR – Gaseous Oxygen only - Depending of the relative valuation of capital and power costs

AIR PRODUCTS

Introduction to Different Cryogenic Air Separation Process

Air Separation Process
Conventional Design (mit Einblaseturbine)

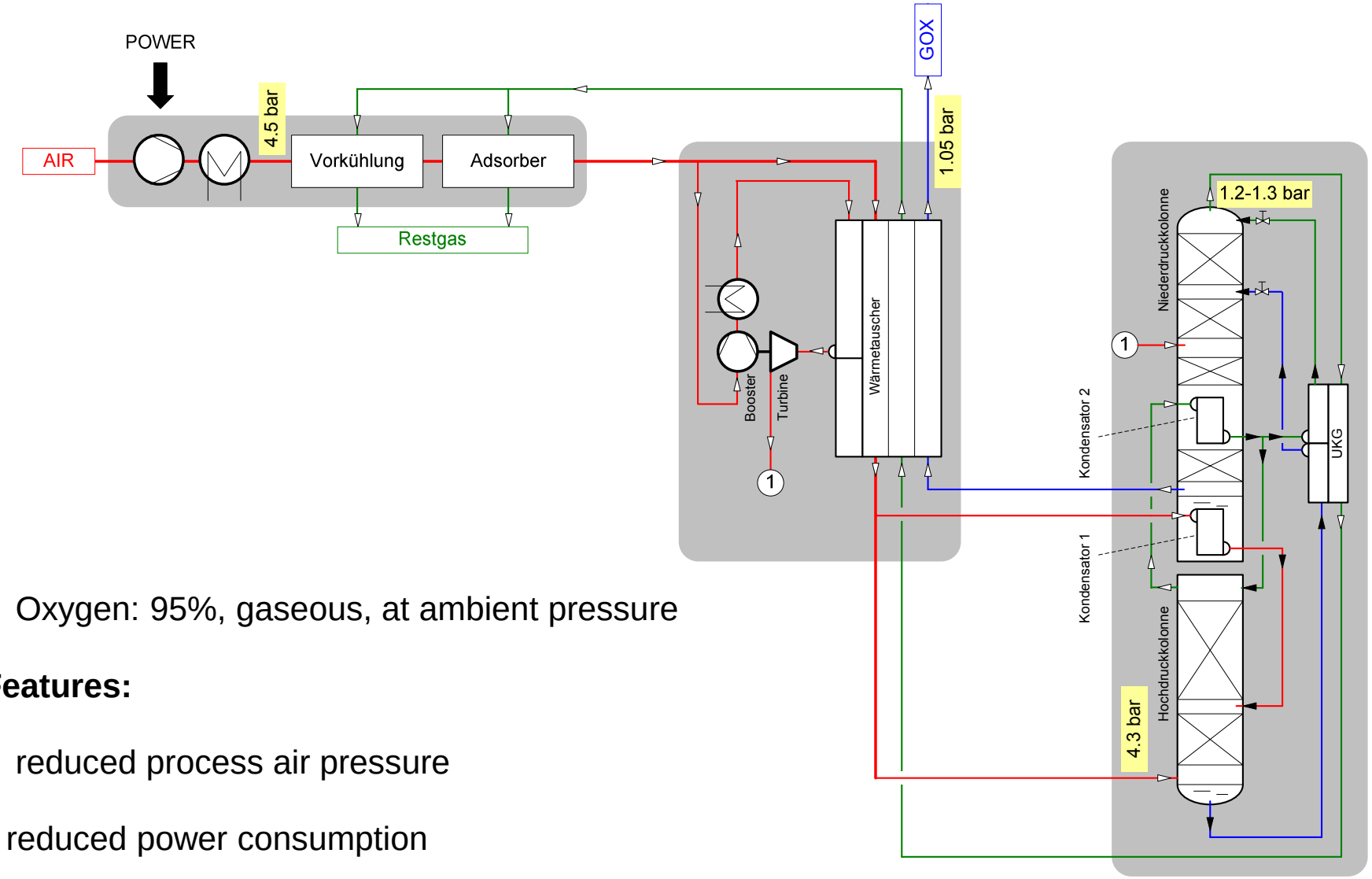


- Oxygen: 95%, gaseous, at ambient pressure

Features:

- PNitrogen: up to 30% of airflow available

Air Separation Process
Advanced Alternative Design ("Dual Reboiler"-Design)

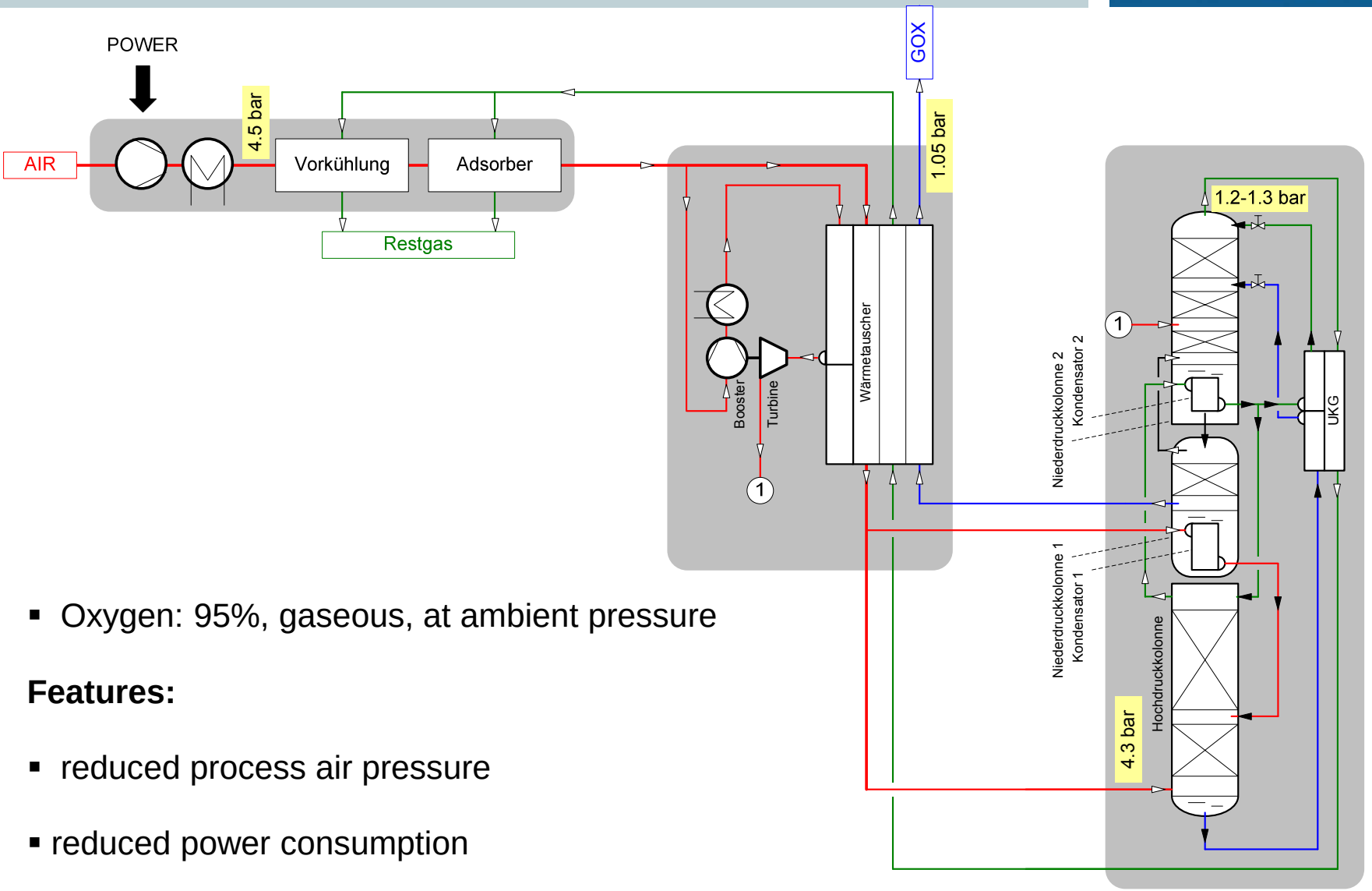


- Oxygen: 95%, gaseous, at ambient pressure

Features:

- reduced process air pressure
- reduced power consumption

Air Separation Process
Advanced Alternative Design (3-column Design)



- Oxygen: 95%, gaseous, at ambient pressure

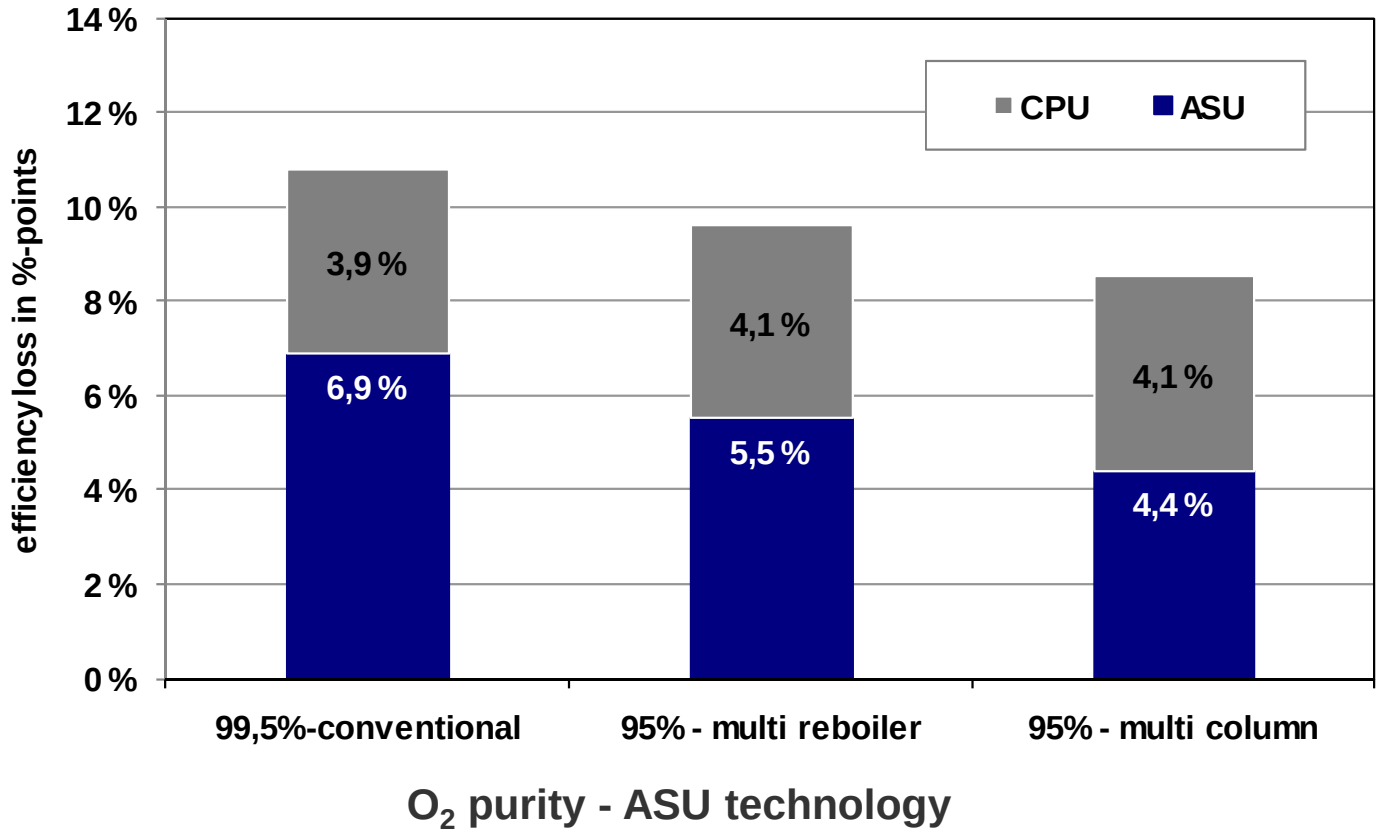
Features:

- reduced process air pressure
- reduced power consumption

Energy demand for ASU and CO_2 separation

Technische Universität Hamburg-Harburg

Boundary conditions: capture rate = 90 %, CO_2-purity > 96%, 87 % of oxygen delivered by ASU, South African hard coal, 2 % leakage air



Overall net efficiency increase by decreased O_2 purity by approx. 2.3 %-points

► Impact of impurities on the CO_2 concentration

What are the remaining issues…

- ***~10,000 TPD of O_2 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***

CO_2 Processing Unit

WHAT ARE THE KEY ISSUES IN DETERMINING THE DESIGN PRINCIPLES OF A CO2 PROCESSING UNIT

Challenges to CO_2 Processing Unit

- ***The CO_2 processing unit could be very competitive business (an important growth area) for industrial gas companies.***

- ***Challenges are:***
  - Demand of the quality requirements of the CO_2 from the power plant for transport and storage. **<u>What are the Required Specification?</u>**
  - Further recovery of CO_2 from the vent will make oxyfuel more competitive if high recovery of CO_2 is required!
  - Further recovery of energy through integration with ASU or boiler would provide further energy savings.
  - **<u>Need a large scale demonstration of the CO_2 processing unit using impure CO_2 as refrigerant.</u>**

Purification of Oxyfuel-Derived CO2 for Sequestration or EOR

- ***CO_2 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 CO_2 quality requirement!!!***

Air Product's "Sour Compression Process"

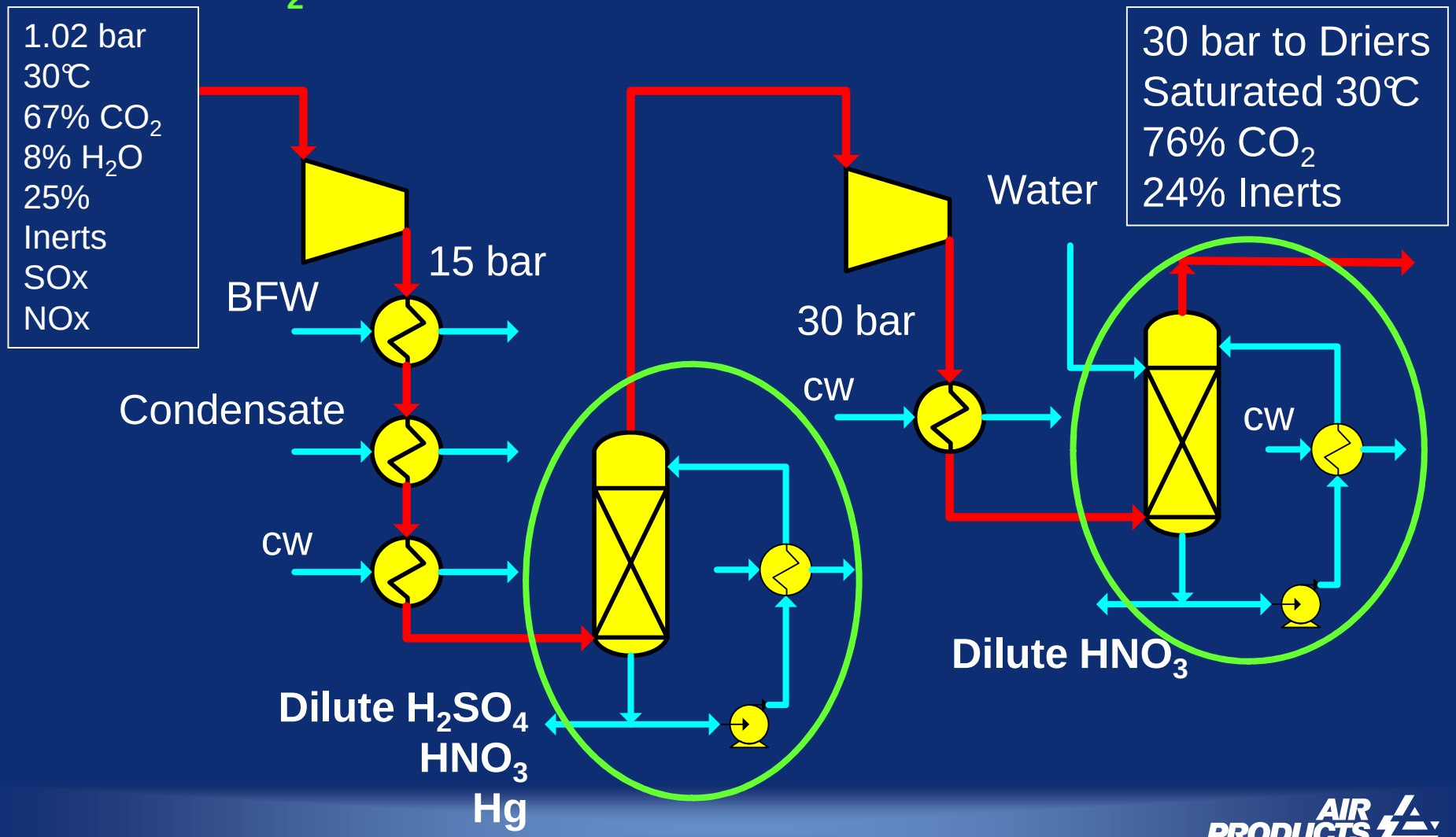
NOx SO_2 Reactions in the CO_2 Compression System

- 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:
  - $NO + ½\ O_2 = NO_2$ (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

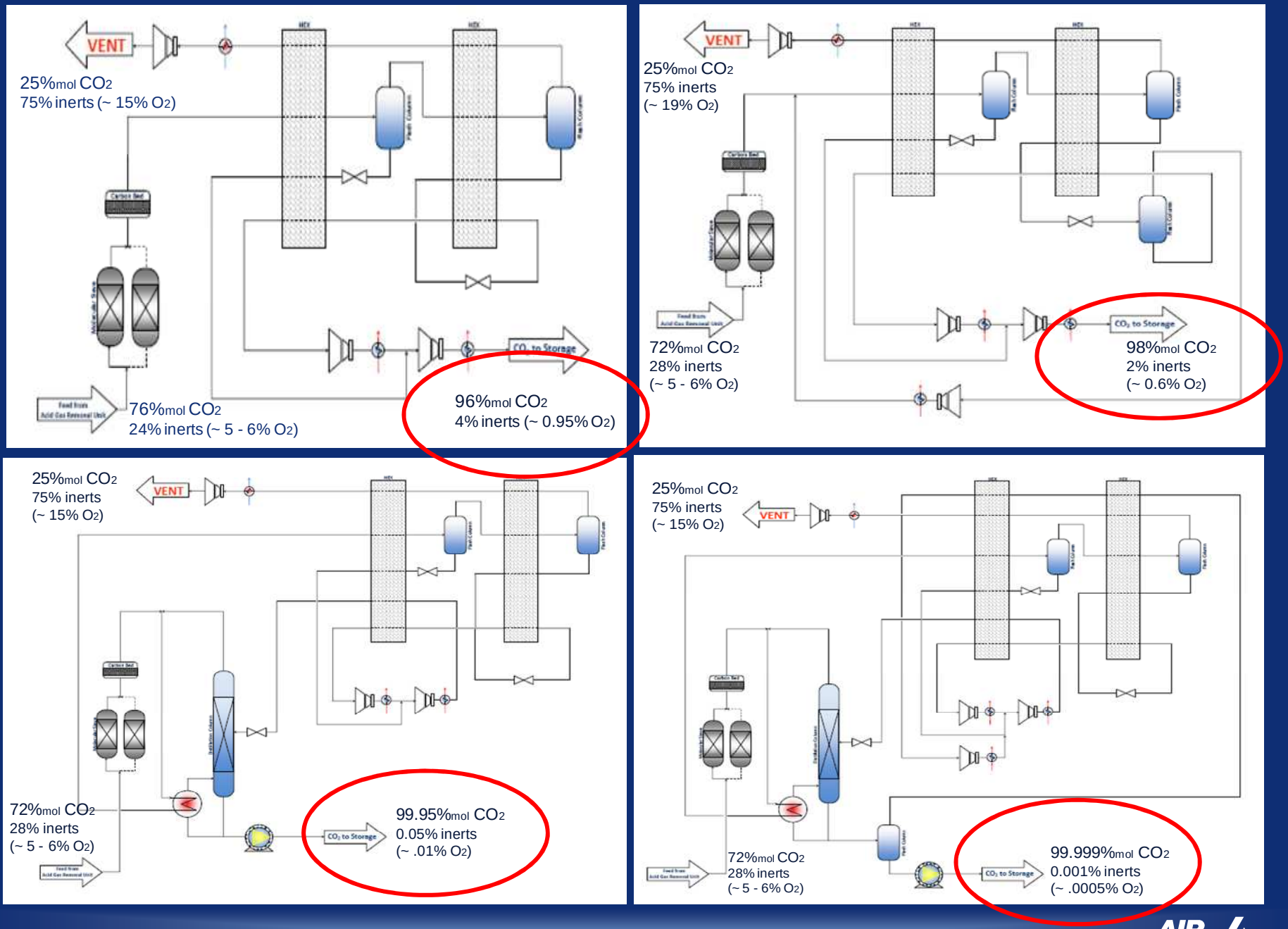
CO_2 Compression and Purification System – Removal of SO_2, NOx and Hg

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



AIR PRODUCTS

Air Product's Suggested Process Design for Various Purity...



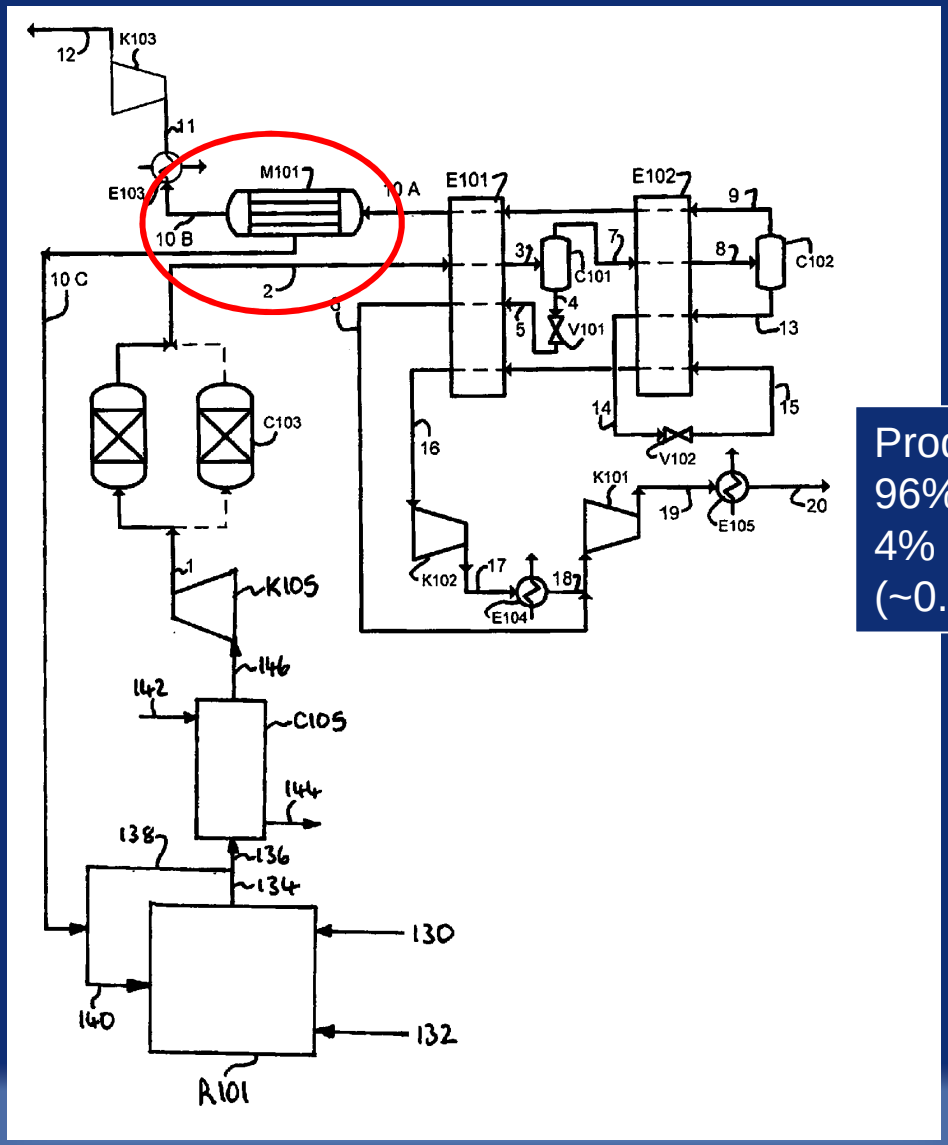
AIR PRODUCTS

Air Product's "Use of Membrane for further recovery of oxygen and CO_2"

AIR PRODUCTS

Use of Membrane to recover CO_2 and O_2 at the vent

Vent:
7% CO_2
93% inerts
(~10% O_2)



Product
96% CO_2
4% inerts
(~0.75% O_2)

AIR PRODUCTS

Issues involving CO_2 purification process

- ***We need to establish what is appropriate and acceptable level of impurities in our CO_2 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 CO_2 (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%.***
  - It should be noted that higher the purity you reduce the CO_2 capture rate.
  - Higher purity means higher CAPEX and OPEX.
- ***Downstream removal of SOx and NOx depends on the taking advantage of the "lead chamber reaction" which naturally occur during wet compression.***
- ***Removal could be achieve by compressions and direct contact acid water wash. This should be demonstrated in the large scale.***

SUMMARY AND CONCLUSIONS

- BURNER AND BOILER DEVELOPMENT
- OXYGEN PRODUCTION
- CO2 PROCESSING UNIT

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:***
  - Heat transfer and flame properties
  - Coal devolatilisatoin and char combustion
  - Slagging, fouling deposition characteristics
  - Emissions (sulphur chemistry, PM and Hg + trace metals)
- ***Development in CFD modelling is an essential tools to help design of future burners and boilers.***

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 CO_2 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***

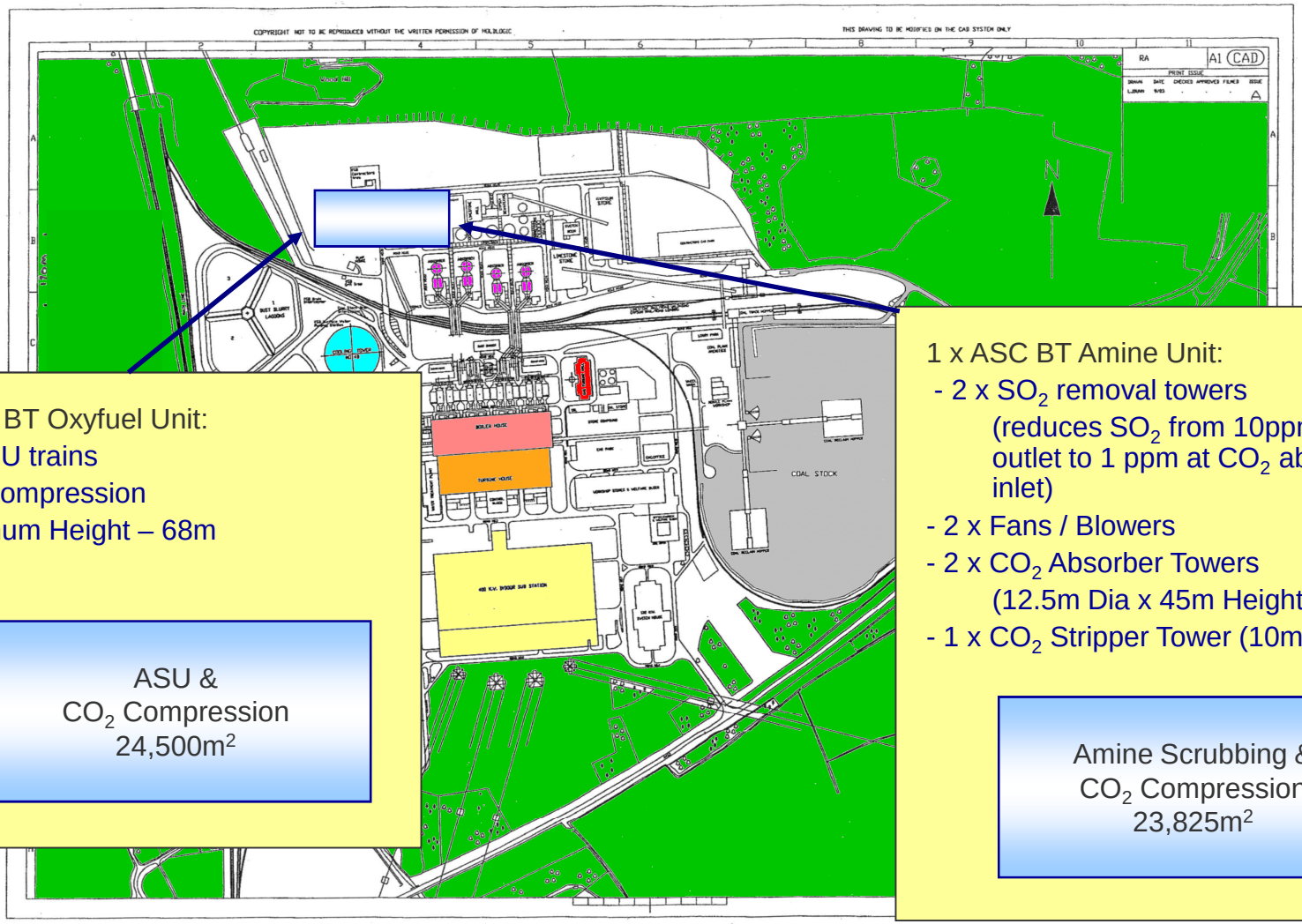
49

Concluding Remarks

- *Oxyfuel Combustion Technology is a viable option for any coal fired power plant with CO_2 Capture.*
- *Oxyfuel Combustion Technology is an option for new build or retrofit cases.*
- ***We need to demonstrate Oxyfuel Combustion Technology to build our confidence.***
- *Business sense, it could have a simple business model for power generation companies wherein the operation of the ASU and CO_2 processing could be outsourced with a long term supply contract from the industrial gas companies.*

Footprint of Capture plant – DTI Project 407

- Oxyfuel and amine scrubbing have similar footprints



1 x ASC BT Oxyfuel Unit:
- 2 x ASU trains
- CO_2 Compression
- Maximum Height – 68m

ASU & CO_2 Compression 24,500m^2

1 x ASC BT Amine Unit:
- 2 x SO_2 removal towers (reduces SO_2 from 10ppm at FGD outlet to 1 ppm at CO_2 absorber inlet)
- 2 x Fans / Blowers
- 2 x CO_2 Absorber Towers (12.5m Dia x 45m Height)
- 1 x CO_2 Stripper Tower (10m Dia)

Amine Scrubbing & CO_2 Compression 23,825m^2

Acknowledgement

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Vince White, Air Products

Thank you

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