THE COAL RESEARCH FORUM.
23rd ANNUAL MEETING AND MEETING OF THE COMBUSTION DIVISION

ASU and CO_2 Processing Units for Oxyfuel CO_2 Capture Plants

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25th April 2012
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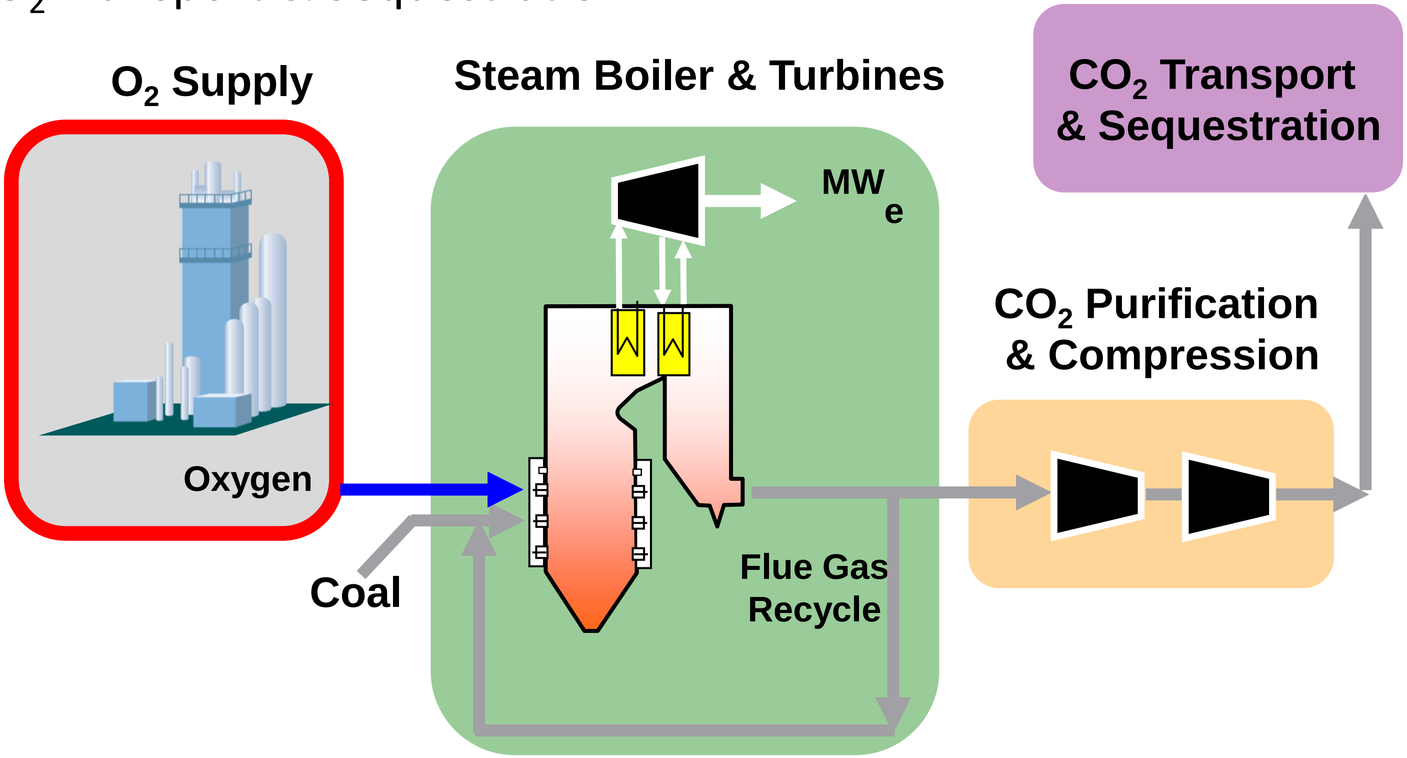
Oxyfuel Combustion Requires…

- Air Separation Units
- Steam Boiler &Turbine
- CO_2 Purification & Compression
- CO_2 Transport & Sequestration



Air Separation Processes

- Adsorption
  - Pressure swing (PSA) and Vacuum swing (VSA)
  - Small scale, up to ~200 tonnes/day O_2 single train
  - Limited purity O_2 (~93%)
- Cryogenic distillation
  - Most flexible – higher purity, liquids
  - Large scale, up to ~5000 tonnes/day O_2
- Other
  - Ion Transport Membrane – in development at ~100 tonnes/day O_2

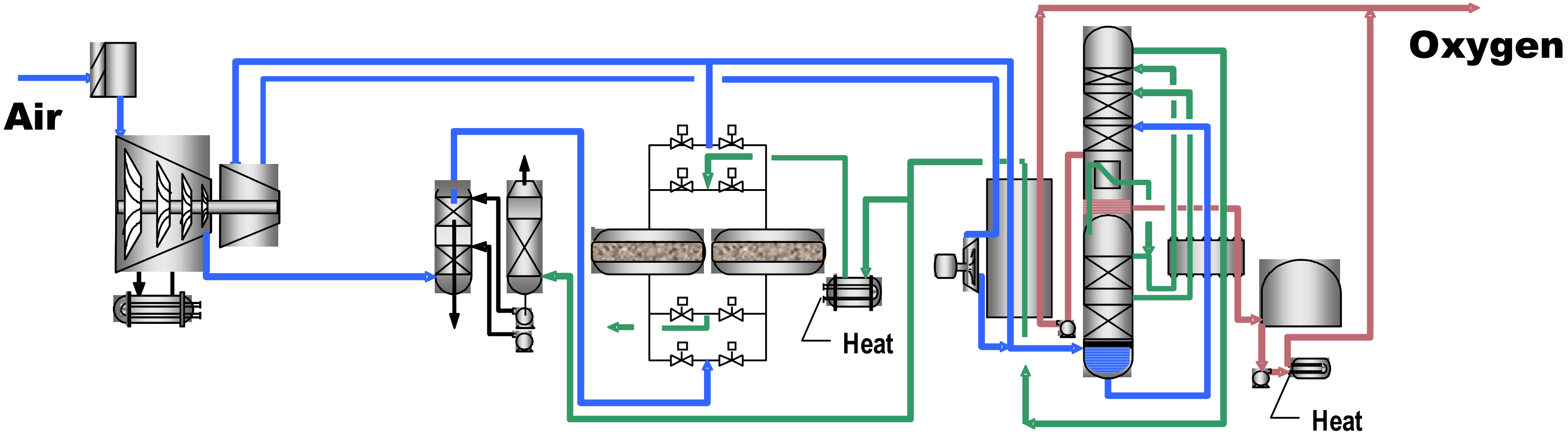
Overview Of The Process

Main and Boost Air Compression

Air Cooling and Pretreatment

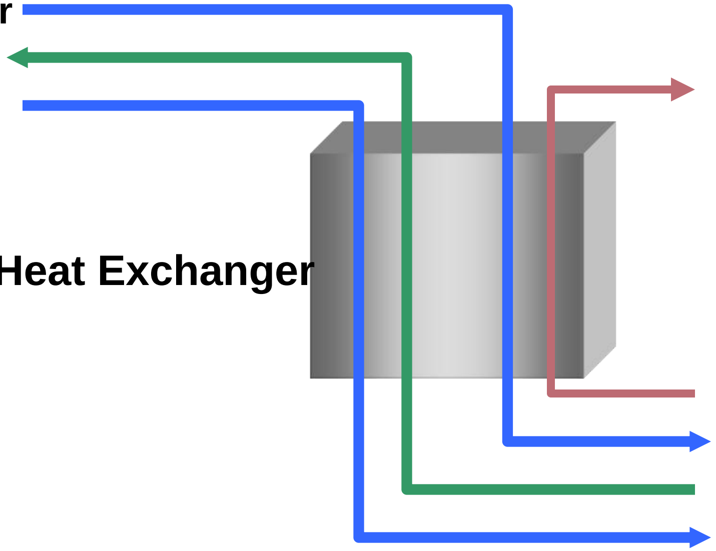
Cryogenic Separation

Storage



Cryogenic Heat Exchange

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

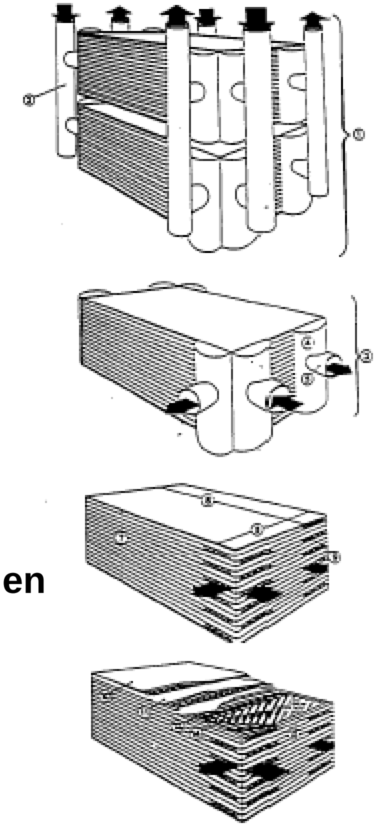


Boost Air
Nitrogen
Main Air

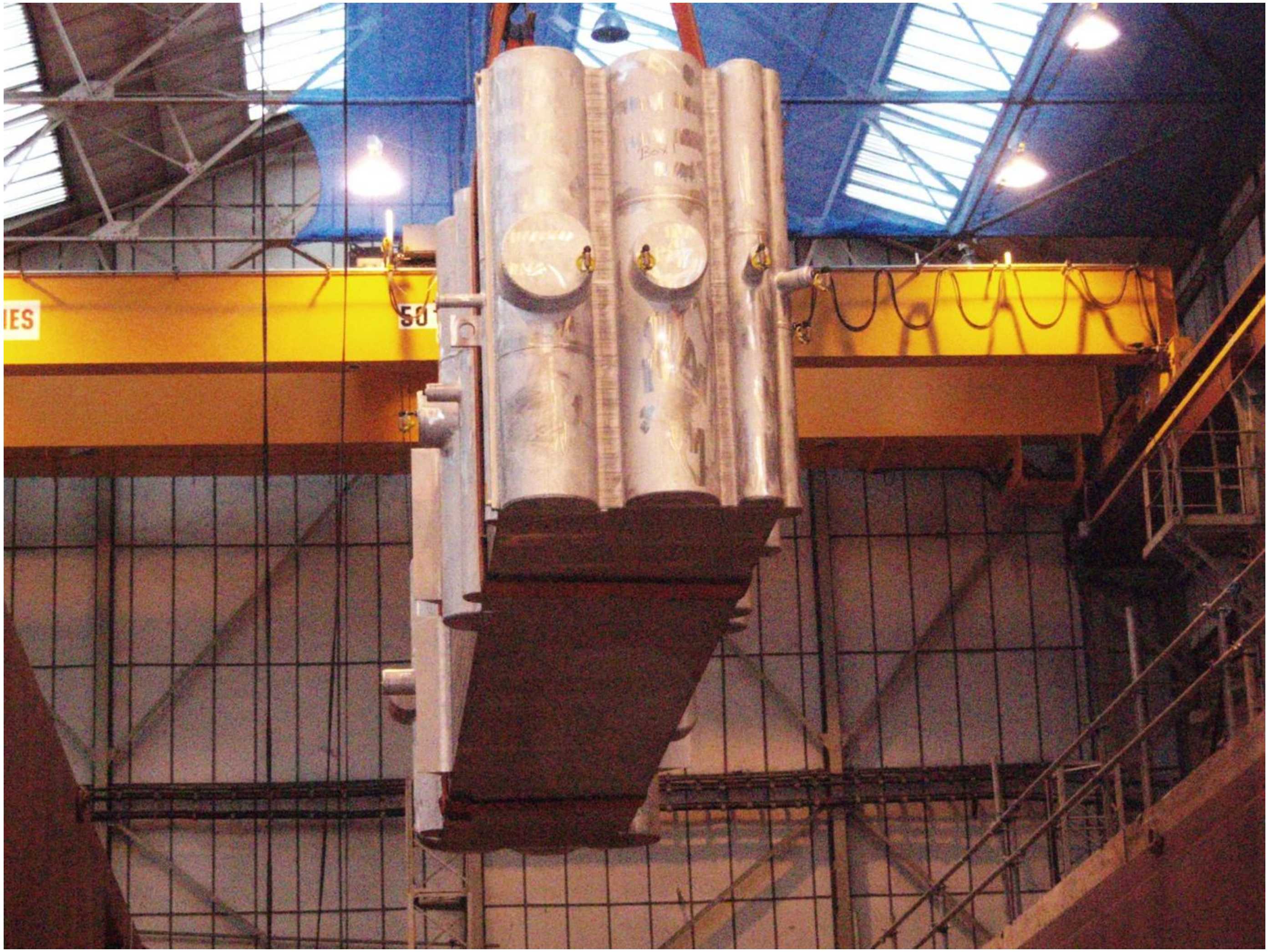
Gaseous Oxygen

Main Heat Exchanger

Liquid Oxygen
“Condensed” Boost Air
Nitrogen
Main Air

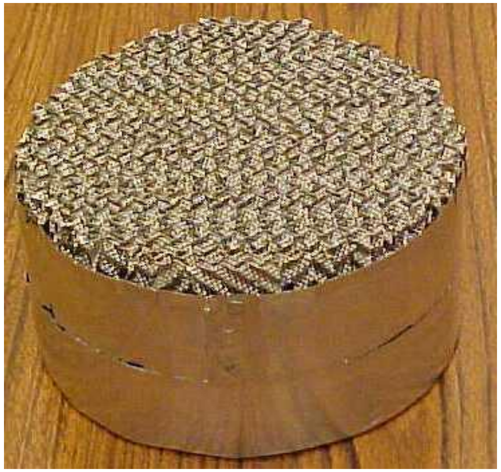


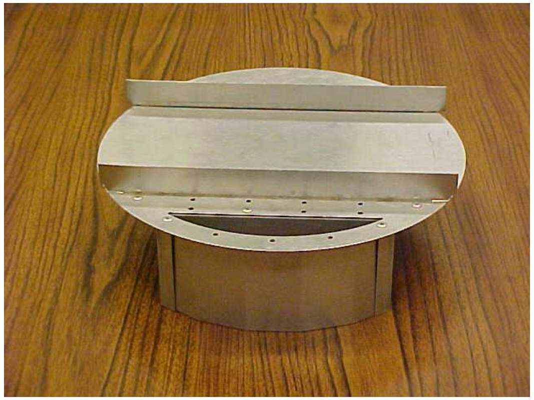
Aluminium Plate-Fin Heat Exchanger Completed Core



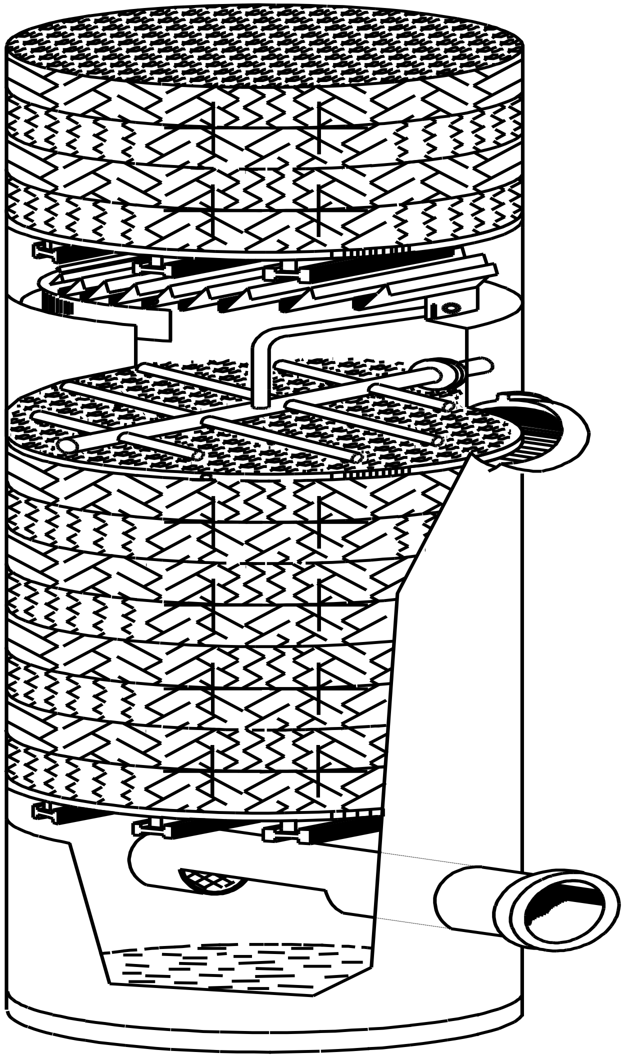
Distillation Technology

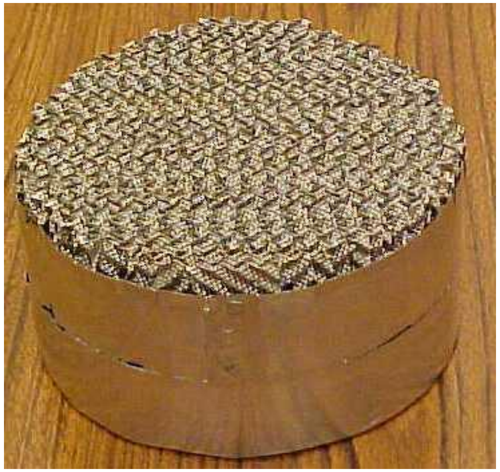
- Structured Packing
  - Lower pressure drop – saves up to 10% of air compressor power
  - Better turndown
  - Higher plant capacity
- Sieve trays
  - Shorter columns

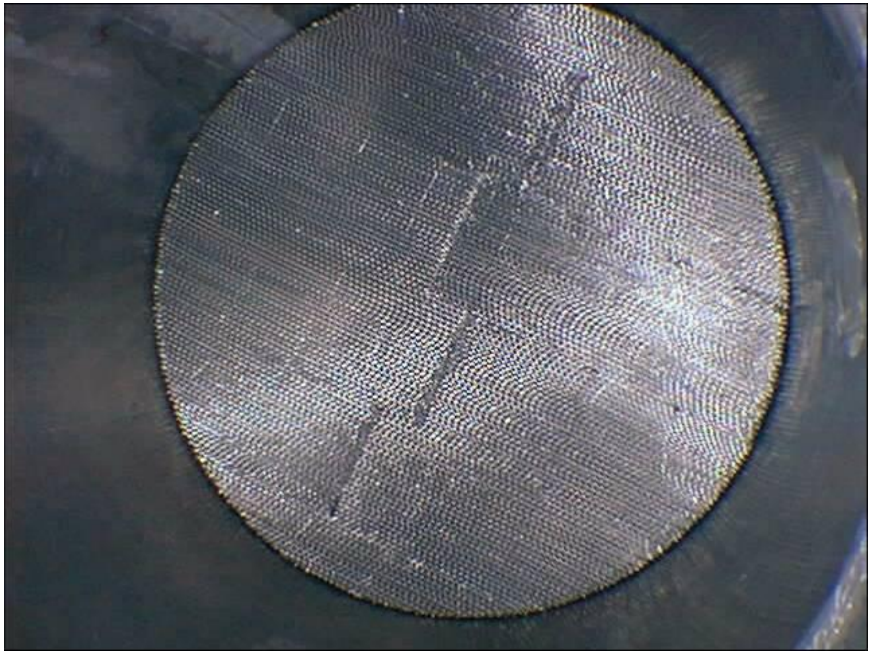




Structured packing



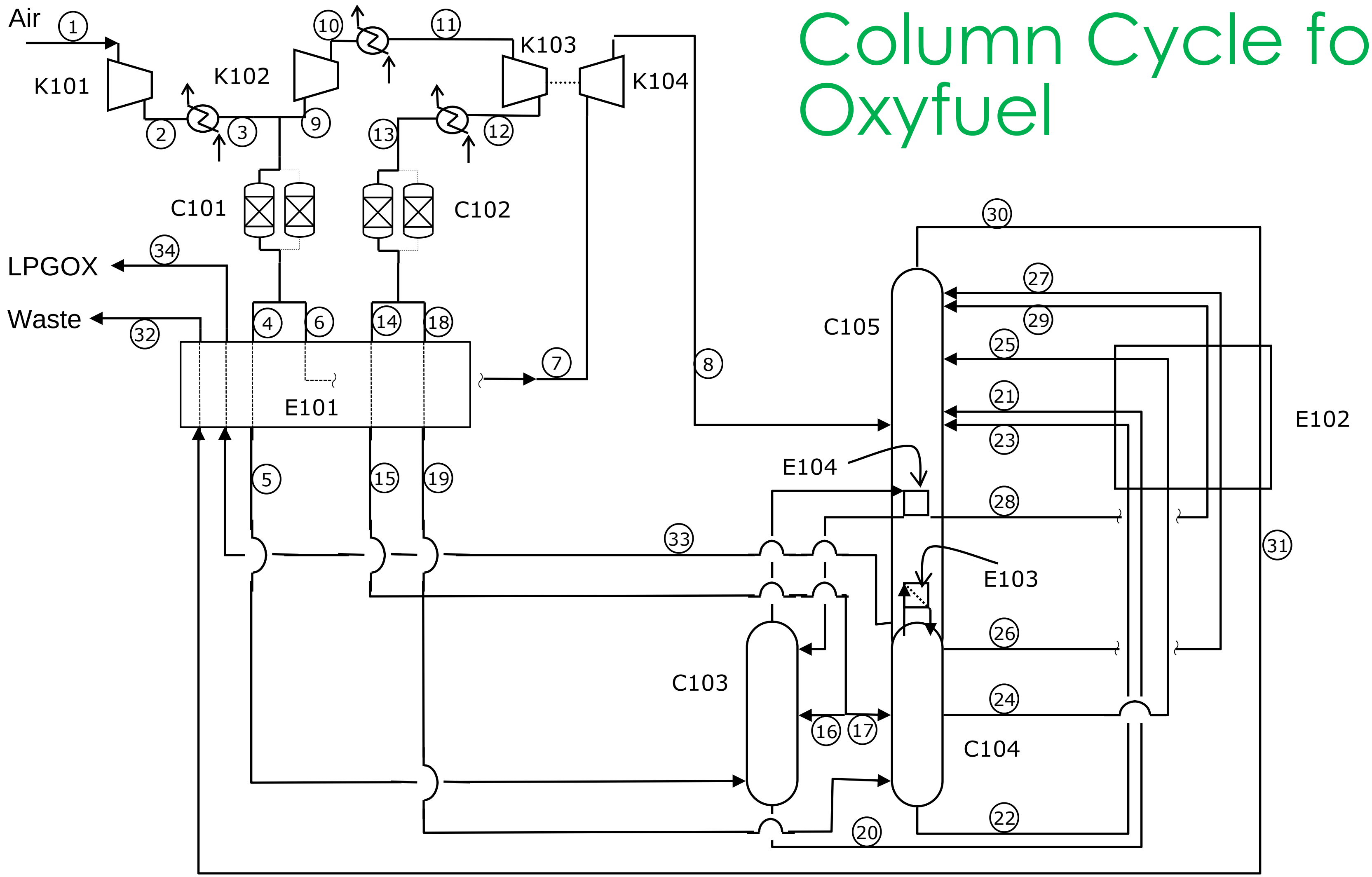




Oxygen Requirements for Oxycoal CO_2 Capture

- Oxygen pressure is low
  - Boiler runs close to atmospheric pressure
- Oxygen purity is low (<97%)
  - Air leaks into boiler, impurities must be removed from CO_2
  - Easier to remove argon from CO_2 than from O_2
- Oxygen demand is large
- 500MWe power plant needs ~10,000 tonnes/day O_2
- No use for co-products
- High efficiency and low capital desirable
  - New opportunities to optimise the ASU

Low Purity, Low Pressure Dual HP Column Cycle for Oxyfuel



Oxycoal "Reference ASU" Cycle

- Integration is not always required or desirable
- With no integration, three column cycle is best
  - Minimum power input, high O_2 recovery
- <u>But</u> three column cycle still ideal for integration
  - Adiabatic compression with heat recovery
  - Optional N_2 at 2.5 bar(a) if it can be used
- <u>So</u> Reference ASU based on three column cycle

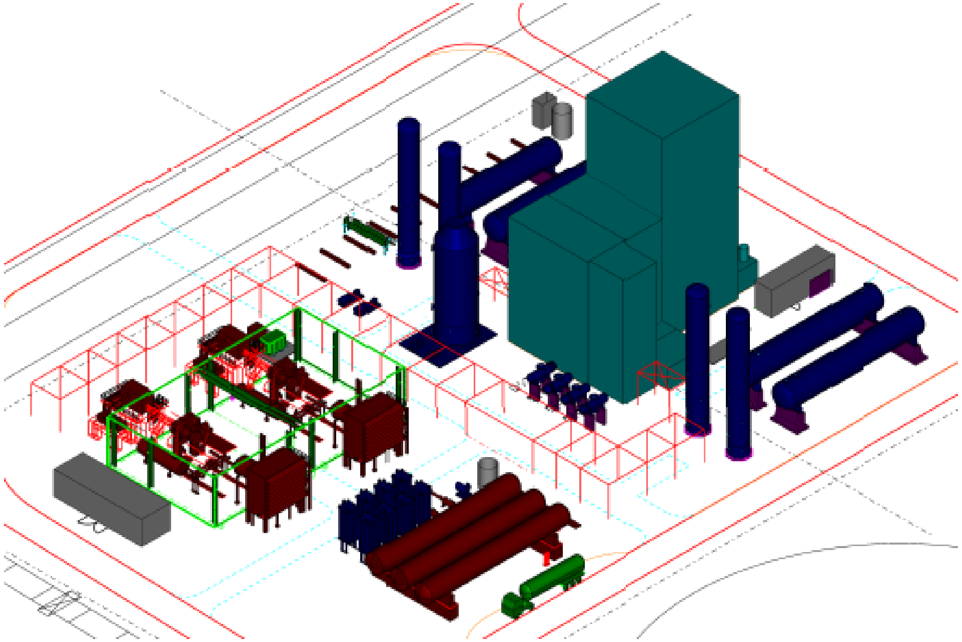
ASU Machinery and Drives

- Significant part of ASU cost (capital and power)
  - Critical to optimise efficiency vs. capital cost
- Likely to reach referenced machinery limits
  - Can use multiple trains for a single cold box
- Centrifugal or axial air compressors
  - Centrifugal up to ~5000 tonnes/day O2
  - Axial up to ~8000 tonnes/day O2

- GT derived units will be even larger
- Electric Motor or Steam Turbine drive (GT unsuitable)
  - Motors simplify operation but may have starting issues
  - Steam turbines more efficient for power generation than mechanical drives – balances extra electrical losses

Oxycoal "Reference ASU"

- Designs developed for a scalable reference plant
- Column diameters within manufacturing capabilities (referenced to 7000 te/d)



Size te/d O_2	Machinery options	Power MW
3,000 – 4,000	Centrifugal 1 or 2 train or axial 1 train	22-33
4,000 – 5,500	Centrifugal 1 or 2 train or axial 1 train	30-45
5,500 – 7,000	Centrifugal 2 train or axial 1 train	41-58
7,000 -10,000	Centrifugal or axial 2 train	53-82

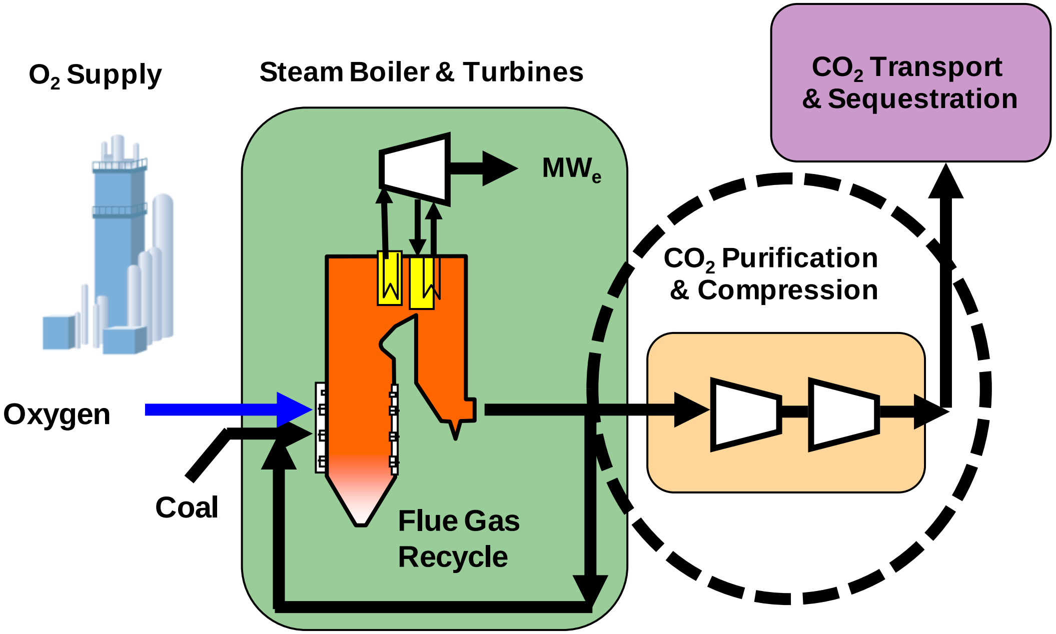
Oxycoal ASU Flexibility

- Turndown limited by compressors not cold box
  - Normally 75-100%
  - Can increase range with efficiency penalty
  - More compression trains or multiple plants give wider, more continuous range
- Rapid ramping possible
  - Dynamic modelling: 5% / minute within ± 2% purity
  - Model predictive control (MPC) will be used
- Instantaneous back-up system
  - For plant trip and peak shaving
  - ASU make liquid for tank refill

Conclusions

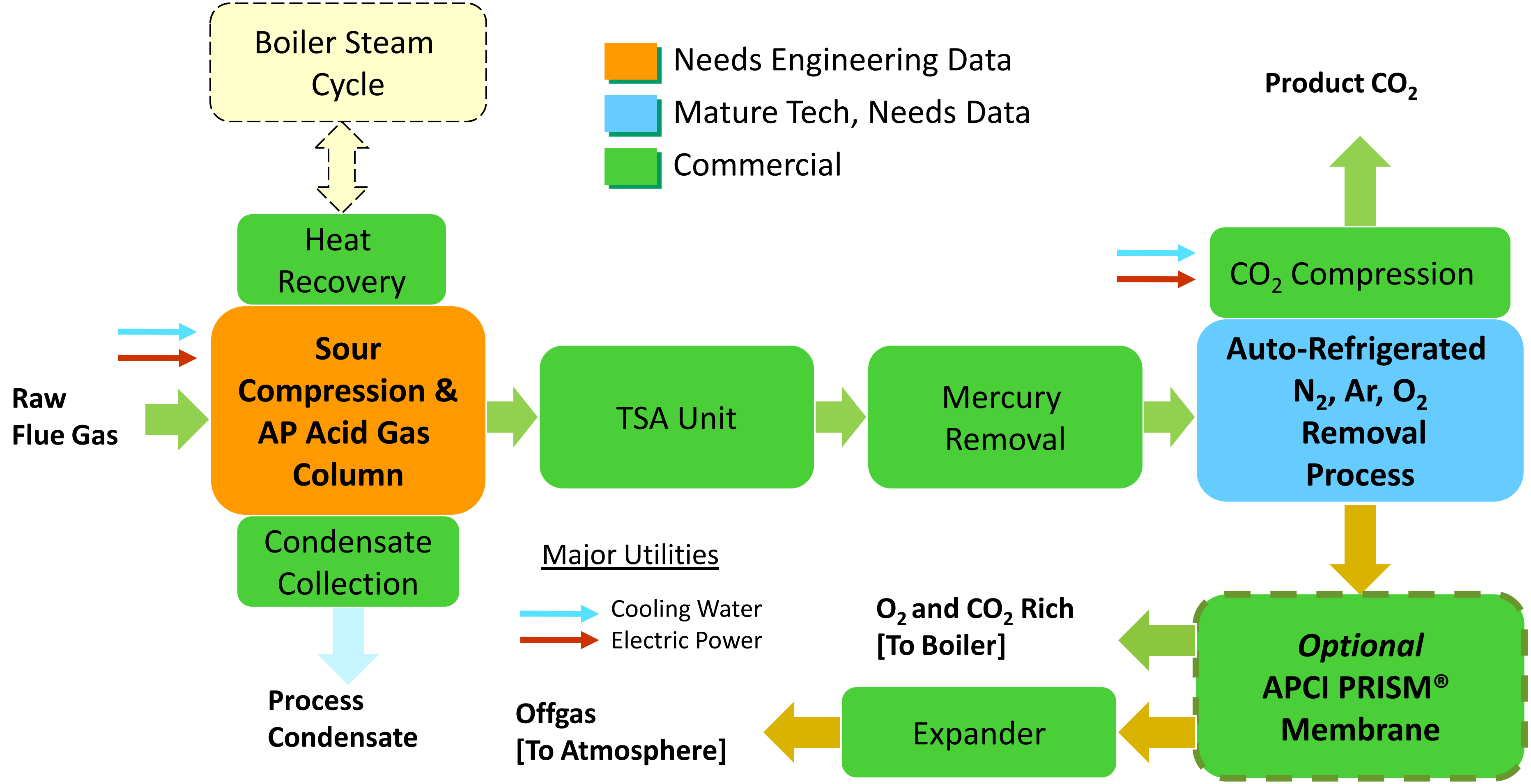
- Air Products Oxycoal ASU has low specific power
  - with or without power cycle integration
- Integration needed to get lower specific power
  - boiler modification & novel expanders
- Single cold box to 10,000 te/d O_2 - modest scale-up
- Single train machinery up to about 8,000 te/d O_2
- Rapid load change possible
- Heat integration beneficial – depends on specifics

Oxyfuel CO_2 Purification



- Oxyfuel combustion of coal produces a flue gas containing:
- $CO_2 + H_2O$
- Any inerts from air in leakage or oxygen impurities
- Oxidation products and impurities from the fuel (SOx, NOx, HCl, Hg, etc.)
- Purification requires:
  - Cooling to remove water
  - Compression to 30 bar: integrated SOx/NOx/Hg removal
  - Low Temperature Purification
    - Low purity, bulk inerts removal
    - High purity, Oxygen removal
  - Compression to pipeline pressure

Air Products Oxy-Fuel CO_2 Capture and Purification – with Air Products PRISM® Membrane



Air Products' CO_2 Purification and Compression Technology for Oxyfuel

Sour Compression SOx, NOx, Hg Removal

- SOx/NOx removed in compression system
    - NO is oxidised to NO_2 which oxidises SO_2 to SO_3
    - The Lead Chamber Process
- FGD and DeNOx systems
    - Optimization
    - Elimination
- Low NOx burners are not required for oxyfuel combustion
- Hg will also be removed, reacting with the nitric acid that is formed

Auto-Refrigerated Inerts Removal Ar, N_2, O_2

- Removal minimises compression and transportation costs.
- Optional O_2 removal for EOR-grade CO_2
- CO_2 capture rate of 90% with CO_2 purity >95%
- CO_2 capture rate depends on raw CO_2 purity which depends on air ingress

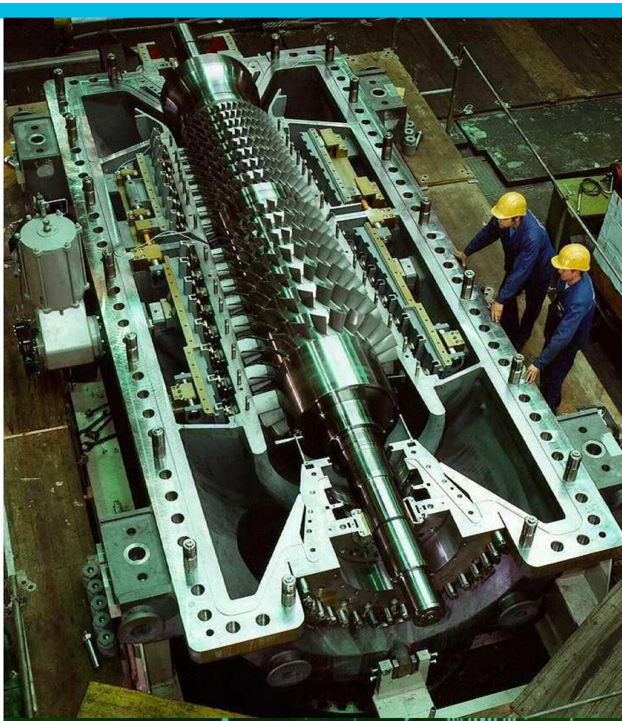
Air Products' PRISM® Membrane For Enhanced CO_2 + O_2 Recovery

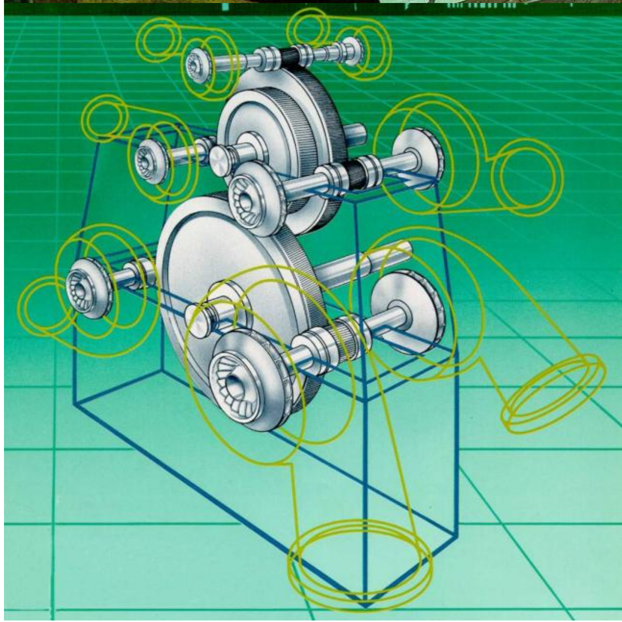
- Inerts vent stream is clean, at pressure and rich in CO_2 (~25%) and O_2 (~20%)
- Polymeric membrane unit – selective for CO_2 and O_2 – in vent stream will recycle CO_2 and O_2 rich permeate stream to the boiler.
- CO_2 capture rate increases to >97% and ASU size/power reduced by ~5%

🟧 Needs Engineering Data
🟦 Mature Tech, Needs Data
🟩 Commercial

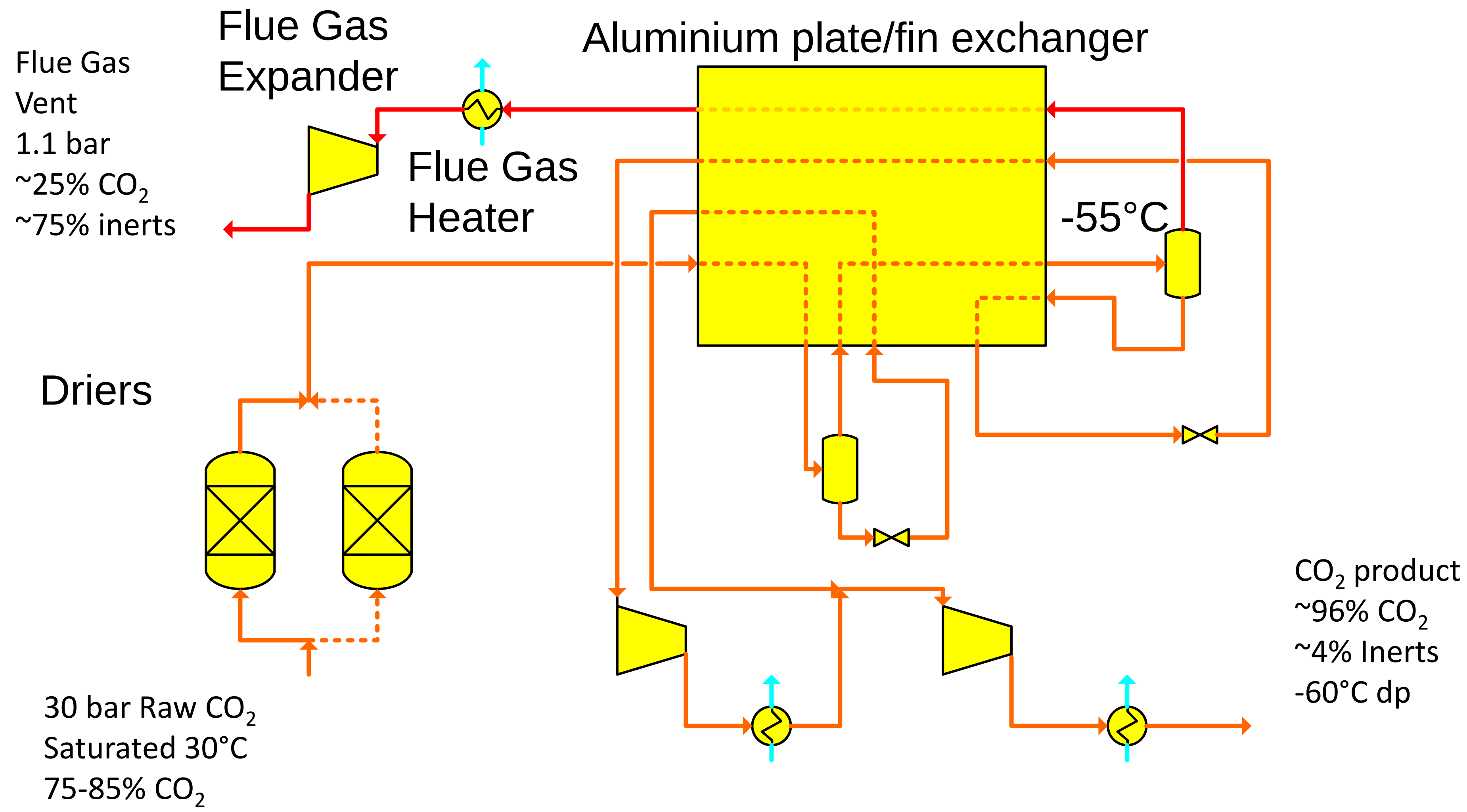
Compression Options to 30 bar

- Axial Compressor (plus inline radial)
  - Higher compression ratios
  - Higher outlet temperature
    - So better integration options
  - Simpler configuration
    - No intercoolers
  - But higher power consumption
    - Offset with integration opportunities
  - Can be single train to ~8-900MWe
- Integrally geared compressor
  - Lower power consumption
  - Less opportunity for integration
  - Might need multiple trains for >500 MWe plants





CO_2 Compression and Purification System – Inerts removal and compression



Flue Gas Vent
1.1 bar
~25% CO_2
~75% inerts

30 bar Raw CO_2
Saturated 30°C
75-85% CO_2

CO_2 product
~96% CO_2
~4% Inerts
-60°C dp

CO_2 Purity and Recovery

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

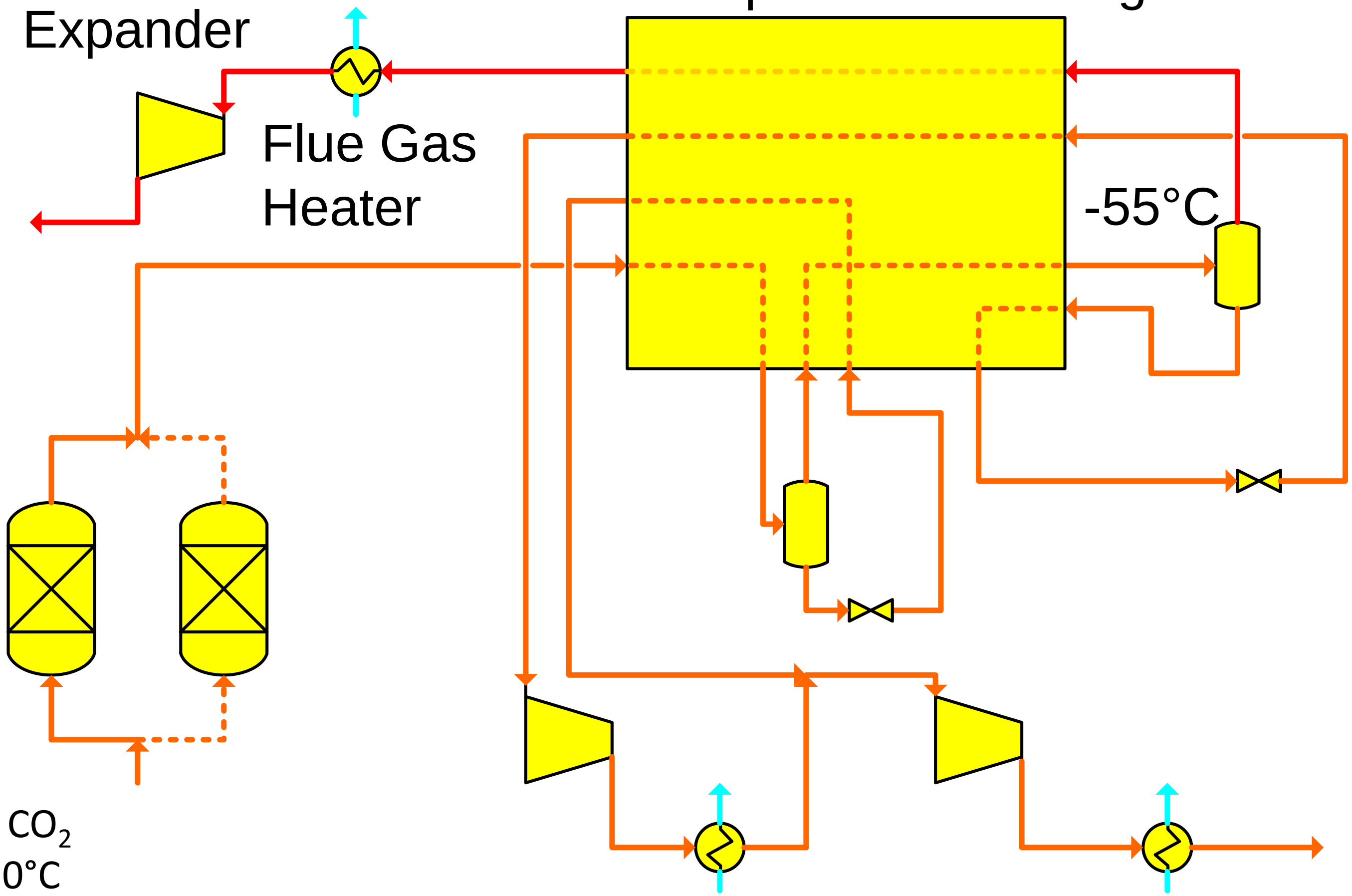
Compression Options from 30 bar to Pipeline Pressure

- Integrally geared compressor only feasible option
- Expander wheels can be integrated onto compressor bull wheel

10-stage Integrally Geared Compressor

Can we improve on ~90% CO_2 Capture?

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



Flue Gas Expander

Aluminium plate/fin exchanger

Flue Gas Heater

-55°C

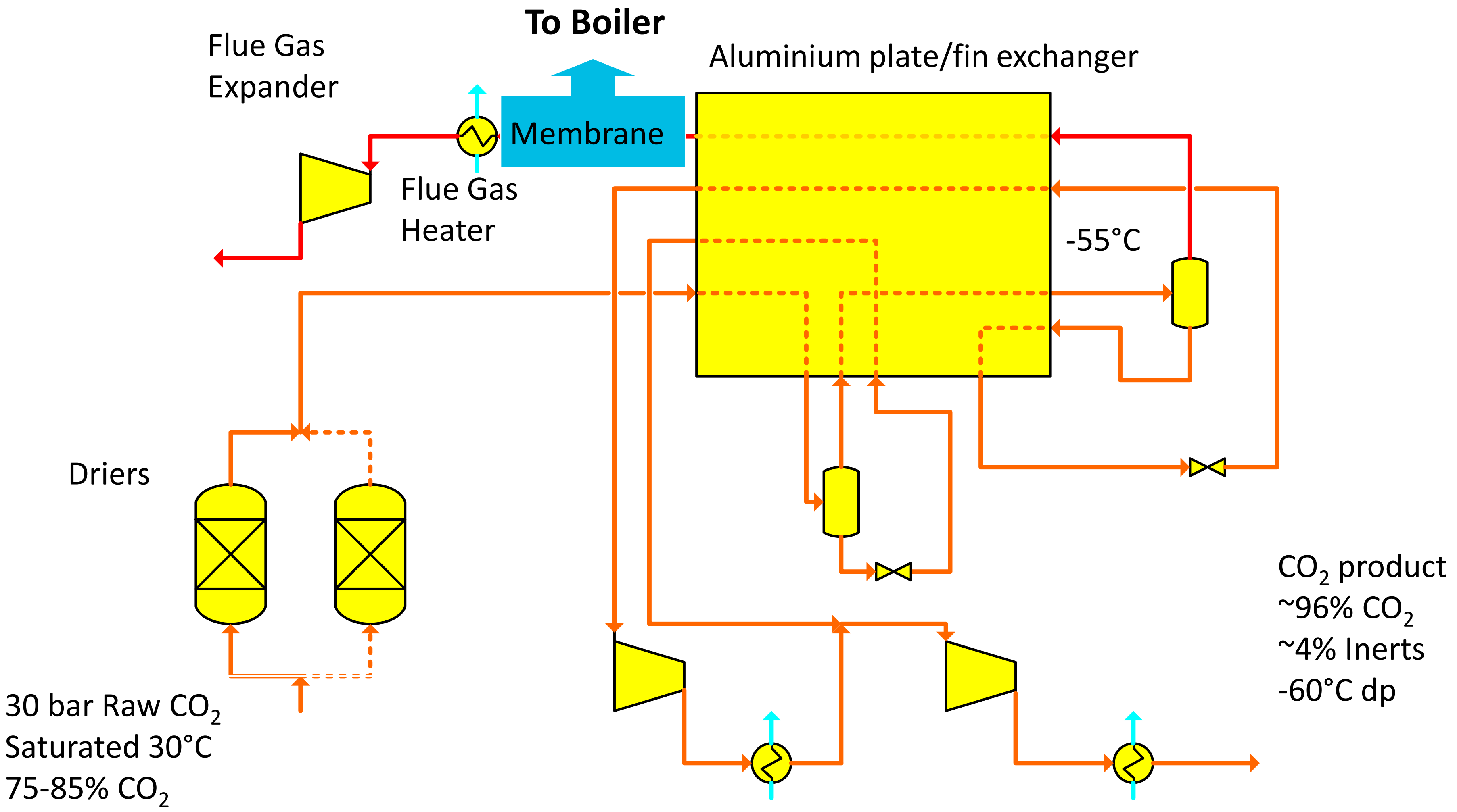
Flue Gas Vent
1.1 bar
~25% CO_2
~25% O_2
~50% N_2

Driers

30 bar Raw CO_2
Saturated 30°C
75-85% CO_2

CO_2 product
~96% CO_2
~4% Inerts
-60°C dp

Air Products Oxy-Fuel CO_2 Capture and Purification – with Air Products PRISM® Membrane



Advantages of Air Products’ CO_2 Purification Technology for Oxyfuel

- 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%

Membrane skid at the Air Products – Vattenfall Oxyfuel Pilot Plant

Path to Large-Scale Demonstration


Photo courtesy of Imperial College

Cylinder fed bench rig


Photo courtesy of Doosan Babcock

160 kW$_{th}$ oxy-coal rig


Photo courtesy of Alstom Power

15 MW$_{th}$ oxy-coal combustion unit


Photo courtesy of Vattenfall

30 MW$_{th}$ oxy-coal pilot plant

Large-Scale (~300 MW) Demo

Imperial College London

London

Batch

DOOSAN Doosan Babcock Energy

Renfrew, Scotland

6 kW$_{th}$ slip stream

DOE Project

Host: Alstom,Windsor, CT

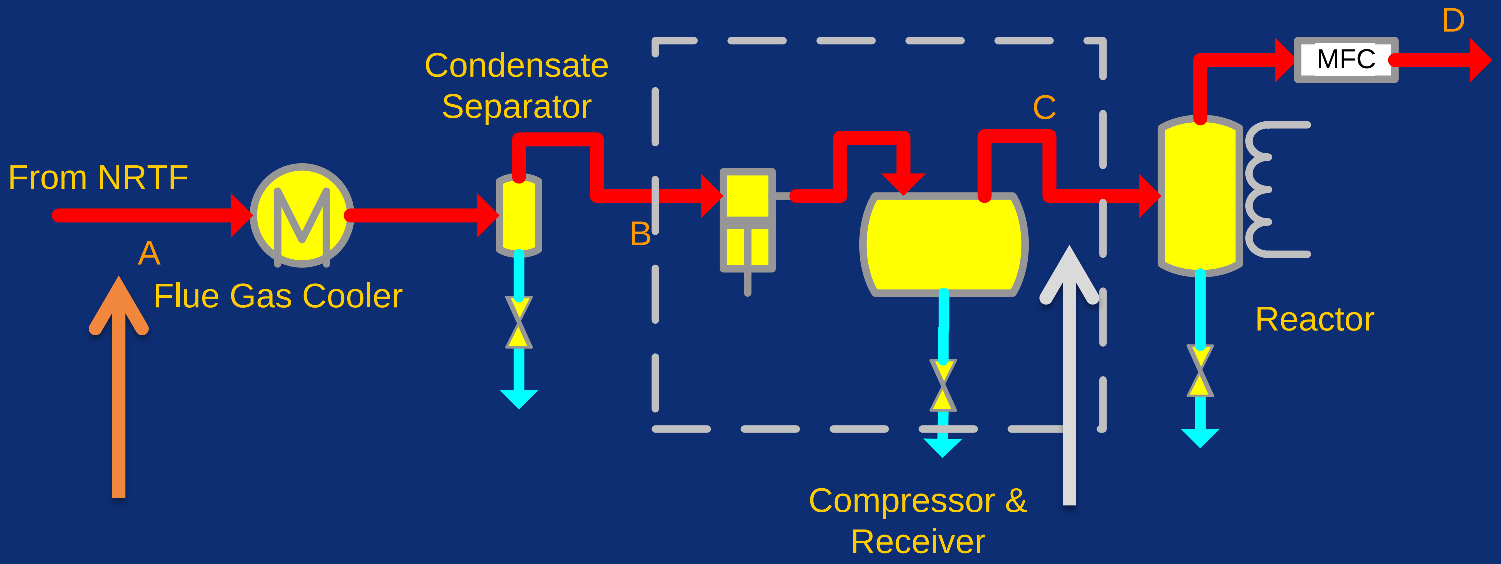
0.3 MW$_{th}$ slip stream

VATTENFALL

Schwarze Pumpe, Germany

1 MW$_{th}$ slip stream

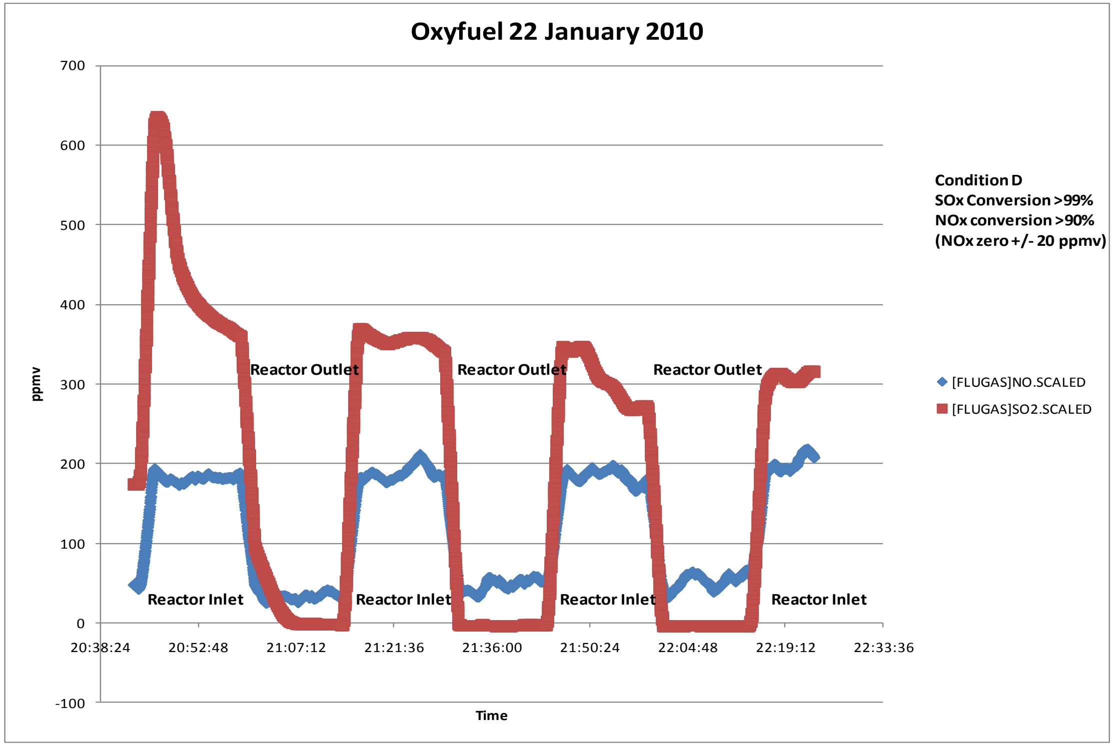
The effect of Pressure on SO_2 and NO Conversion (1 sl/min, 7 and 14 barg)



	14 bar g			7 bar g		
	Inlet (Point A)	After Compressor & Receiver (Point C)	Conversion	Inlet (Point A)	After Compressor & Receiver (Point C)	Conversion
ppm SO2	900	20	98%	950	150	84%
ppm NOx	520	50	90%	390	120	68%

DOE Project: Air Products' Sour Compression PDU – Key Results

- For the overall process, total SO_2 removal was 20-100 % (based on gas compositions).
- For the overall process, total NOx removal was 60-90 % (based on gas compositions).



Condition D
SOx Conversion >99%
NOx conversion >90%
(NOx zero +/- 20 ppmv)

- The effects of variations in the SO_2/NOx feed ratio, column pressure, gas flowrate and liquid recirculation on the reactor performance were explored. Process performance was most sensitive to SO_2/NOx feed ratio, over the range of parameter values investigated.
- SO_2 was removed from the flue gas through both sulfite and sulfate mechanisms.

The Vattenfall – Air Products Oxyfuel CPU Pilot Plant

Air Products' Proprietary Technology Joins World's First Full Demonstration of Oxyfuel CO2 Capture and Sequestration at Vattenfall

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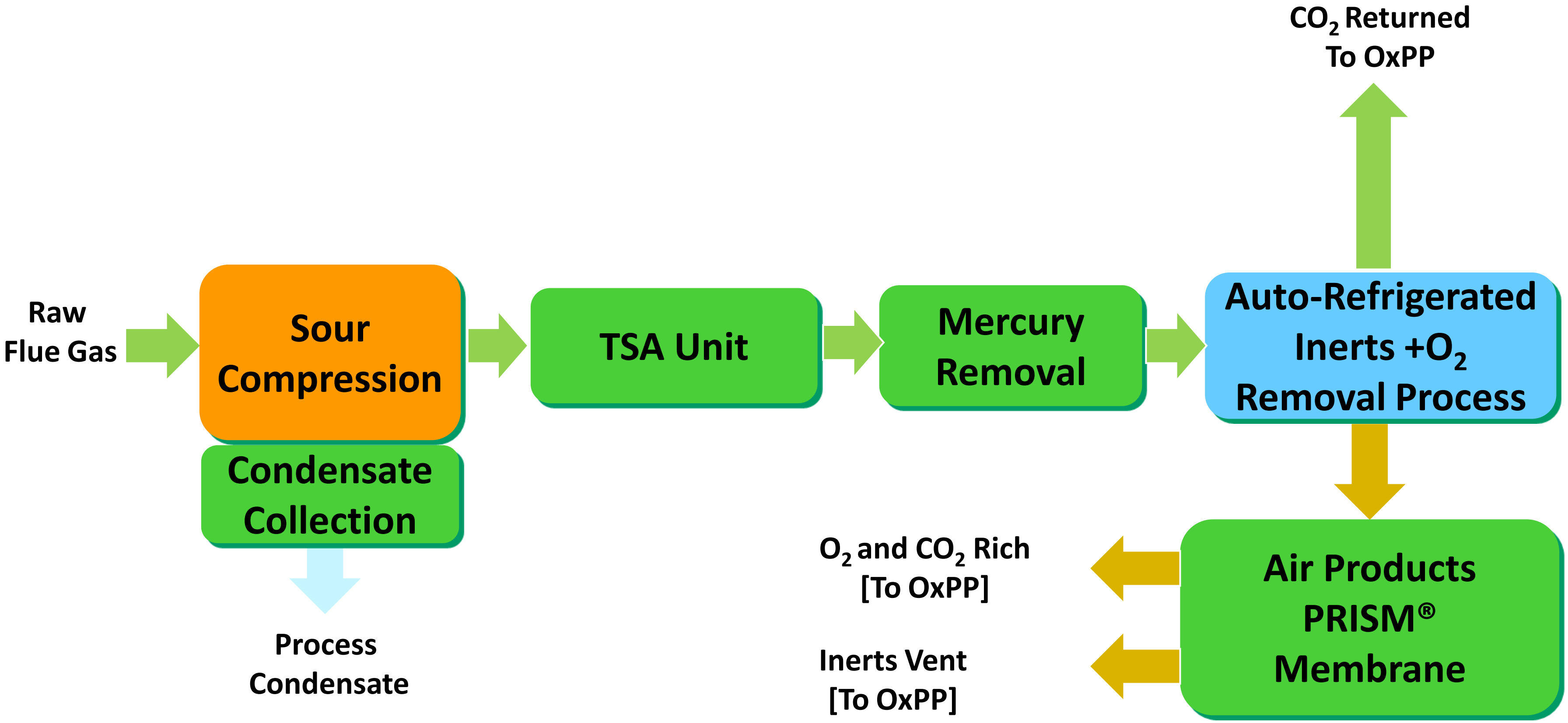
LEHIGH VALLEY, Pa. (March 31, 2009) - Air Products (NYSE: APD) today announced it will play a key role in the world's first full demonstration of oxyfuel carbon capture and sequestration with the signing of an agreement with Vattenfall AB, one of Europe's leading energy companies. Air Products will install its proprietary carbon dioxide (CO_2) capture, purification and compression system at Vattenfall's research and development facility in Schwarze Pumpe, Germany, which is viewed globally as the preeminent CO_2 oxyfuel project. Air Products will focus specifically on the purification and compression of oxyfuel combustion flue gas. The two companies also executed a joint research and development agreement related to the project. Air Products' pilot plant is to be operational at Schwarze Pumpe in December 2010.

Air Products' CO_2 Purification Unit (CPU) Pilot Plant at Vattenfall's Schwarze Pumpe



CO_2 Returned To OxPP

Raw Flue Gas

Sour Compression

Condensate Collection

Process Condensate

TSA Unit

Mercury Removal

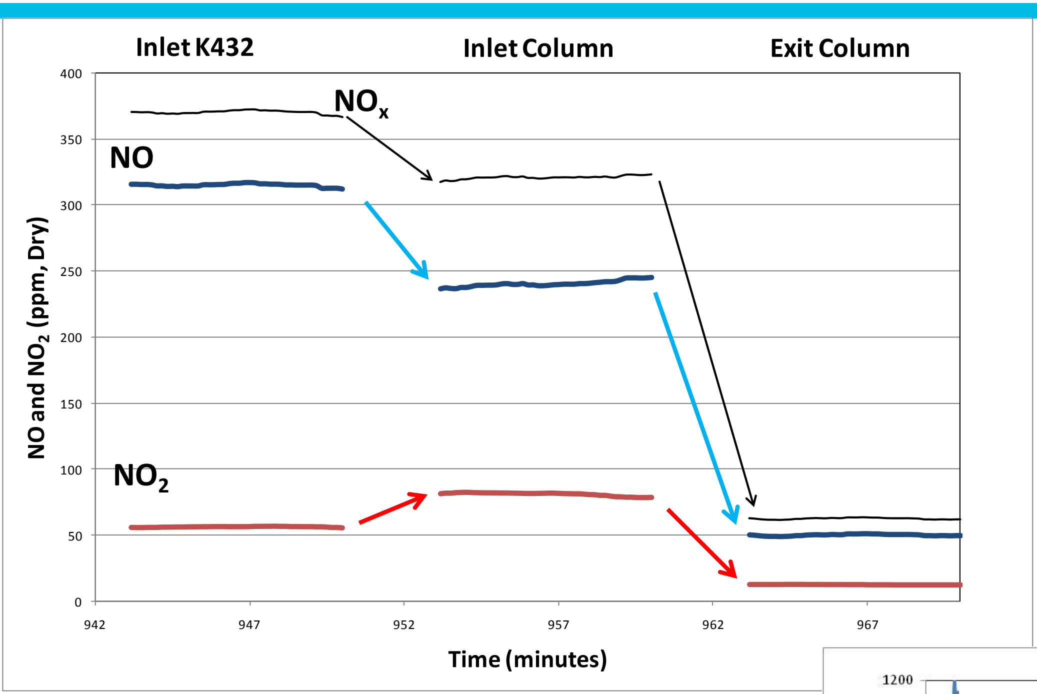
Auto-Refrigerated Inerts +O_2 Removal Process

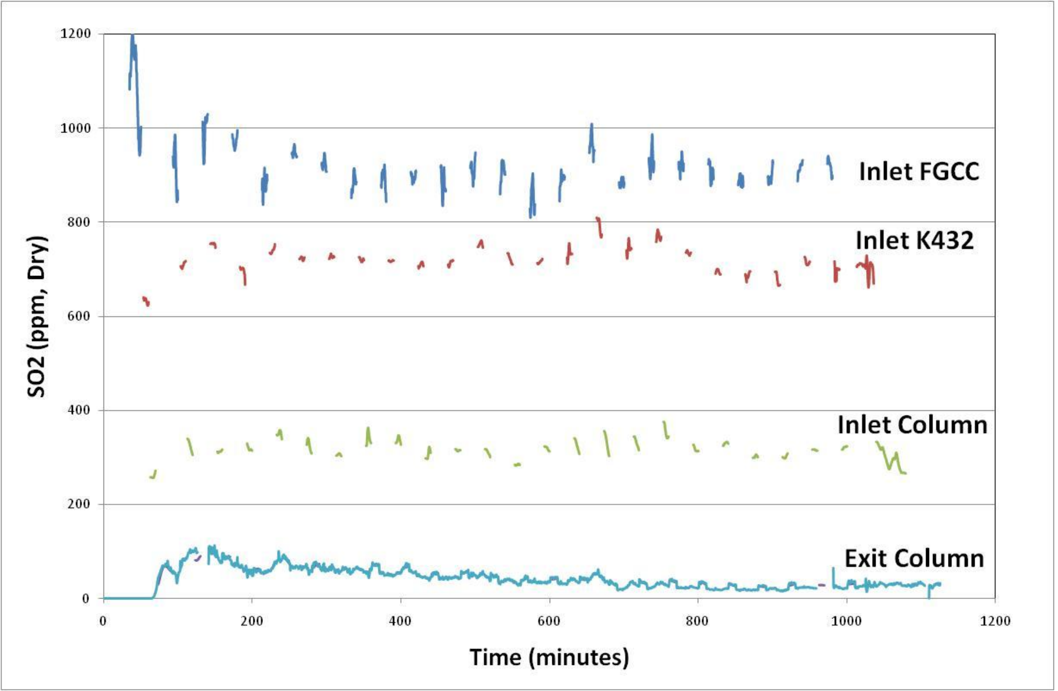
Air Products PRISM® Membrane

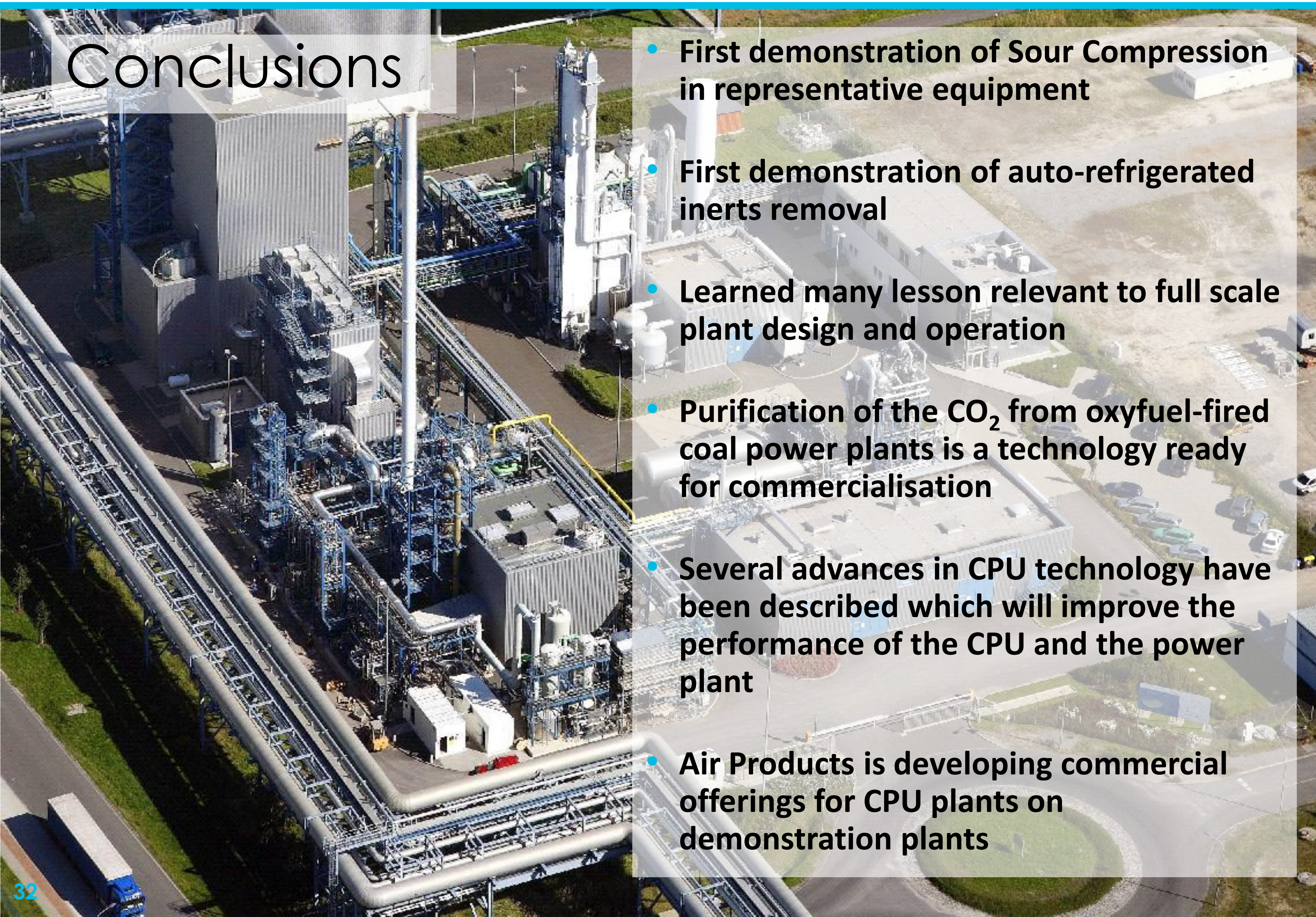
O_2 and CO_2 Rich [To OxPP]

Inerts Vent [To OxPP]

50/50 Flue Gas Mix From Before and After OxPP FGD







Conclusions

- First demonstration of Sour Compression in representative equipment
- First demonstration of auto-refrigerated inerts removal
- Learned many lesson relevant to full scale plant design and operation
- Purification of the CO_2 from oxyfuel-fired coal power plants is a technology ready for commercialisation
- Several advances in CPU technology have been described which will improve the performance of the CPU and the power plant
- Air Products is developing commercial offerings for CPU plants on demonstration plants

Thank you

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