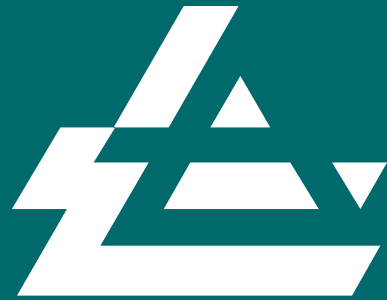


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GCEP Energy Workshop



*Frances C. Arrillaga Alumni Center, Stanford University*

# CO<sub>2</sub> Separation – State of the Art and Future Prospects

Rodney Allam  
Director of Technology

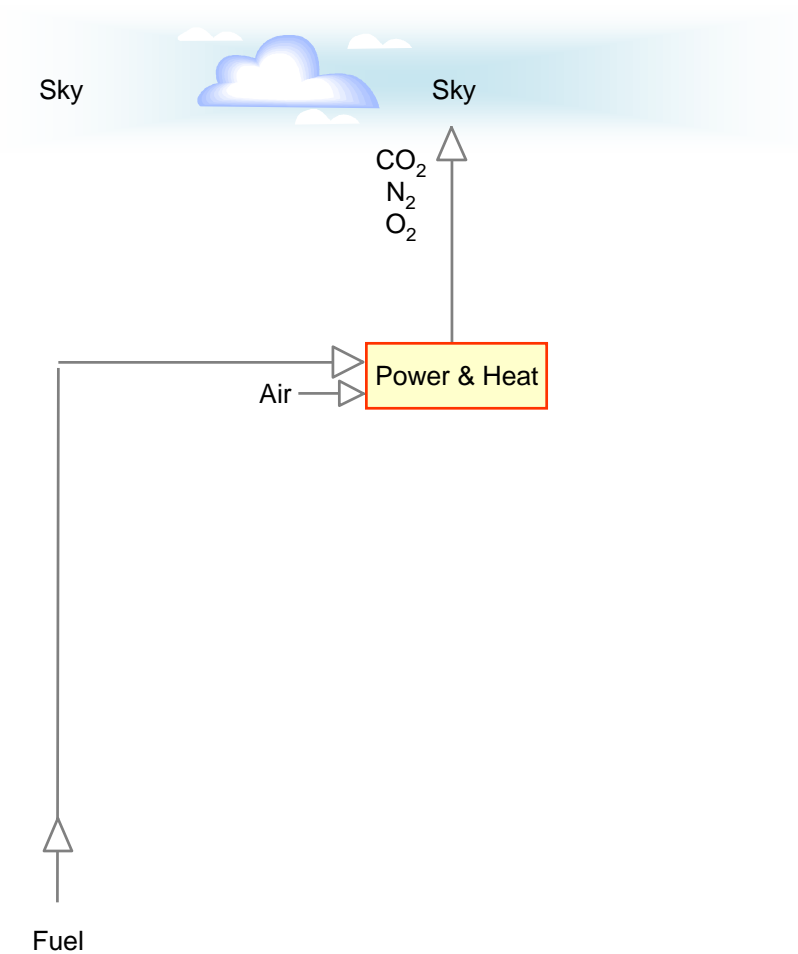


# Overview

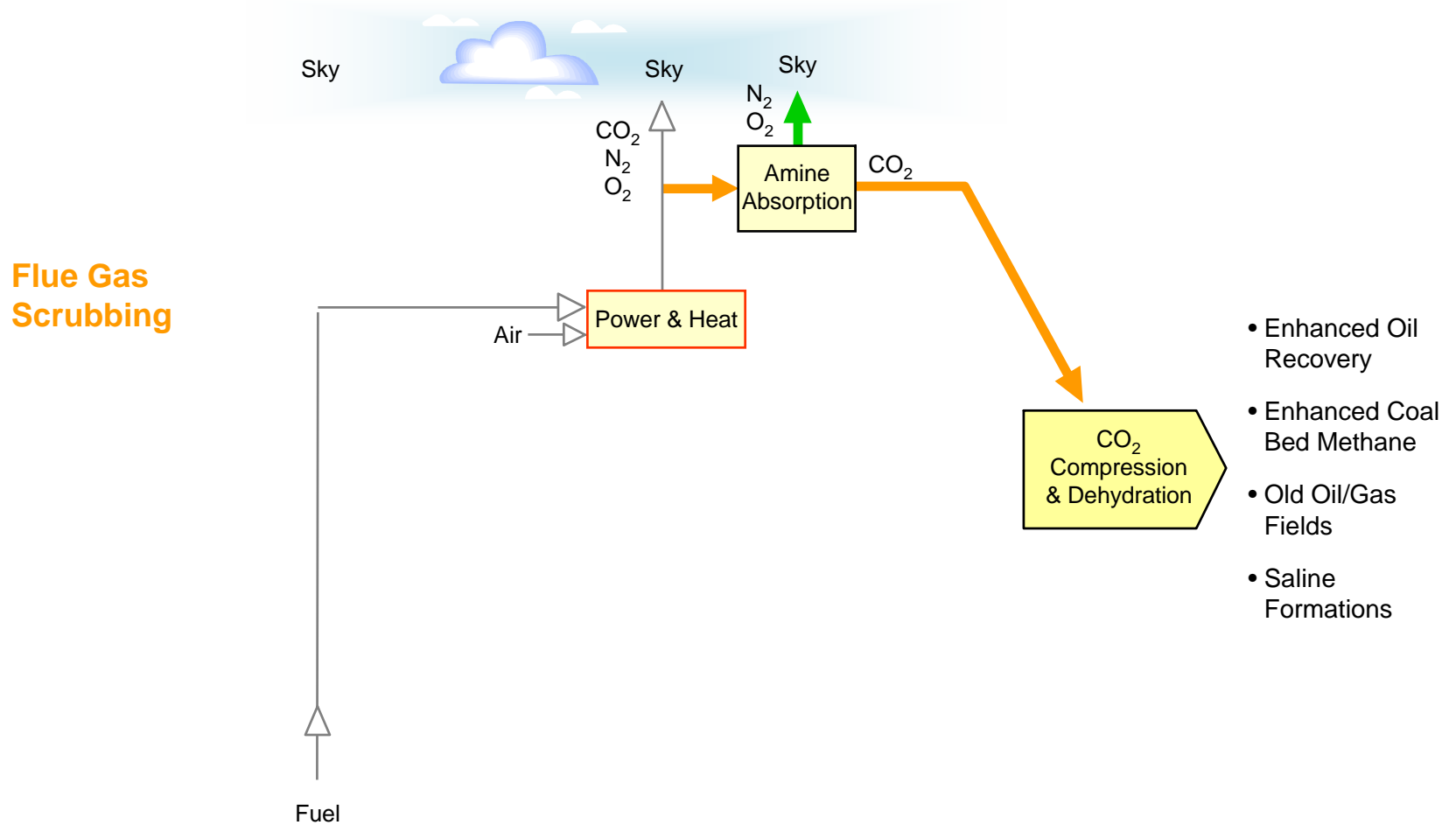
- **This presentation covers CO<sub>2</sub> capture techniques**
  - Flue gas scrubbing
  - Precombustion CO<sub>2</sub> capture
  - Oxyfuel
- **CO<sub>2</sub> separation technologies**
  - adsorption
  - membrane
  - absorption
  - Low temperature (primarily purification and liquefaction)
- **We will deal with options using existing technology together with new techniques requiring further development**

# Carbon Dioxide Management

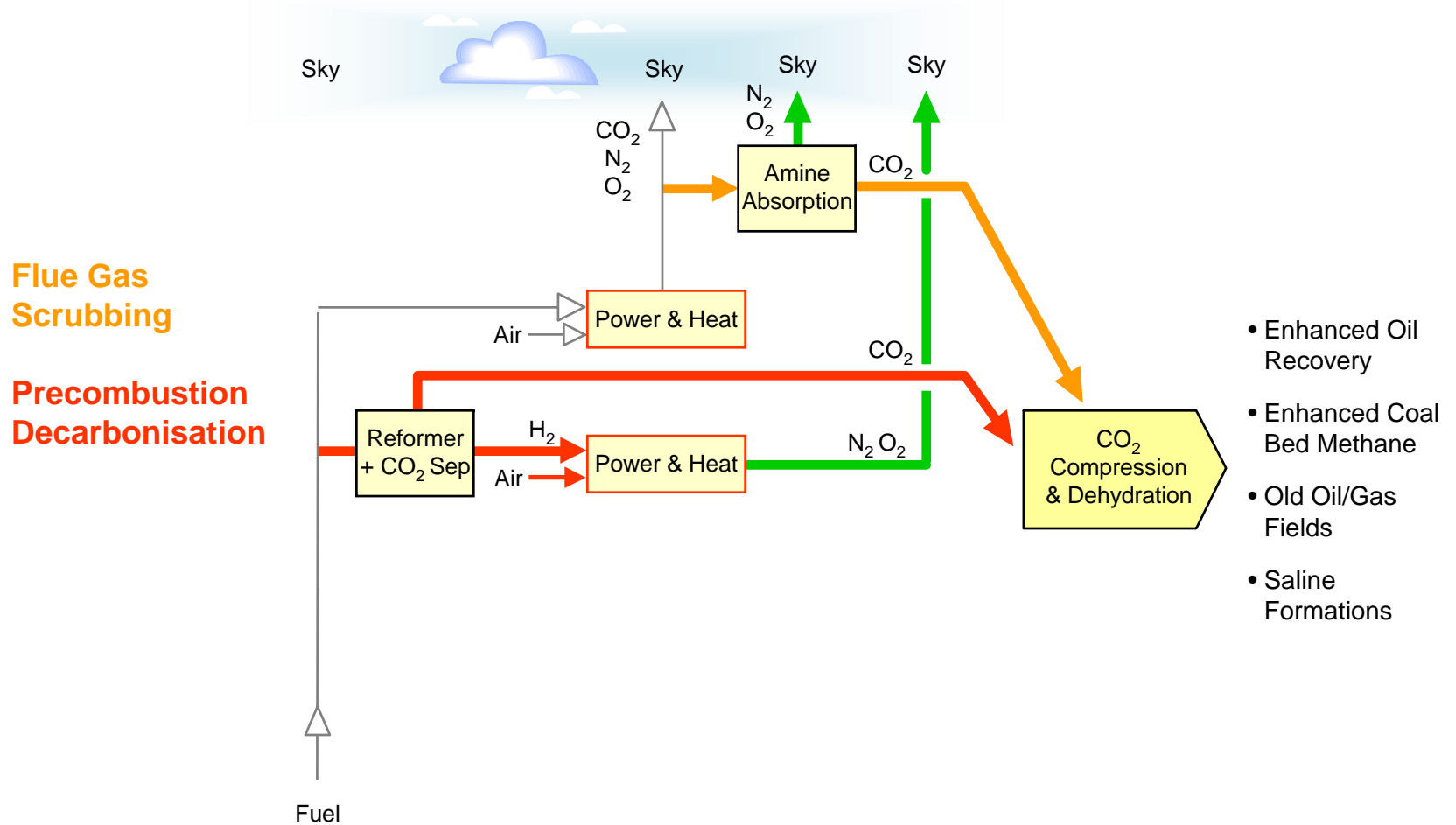
## Reducing CO<sub>2</sub> Emissions



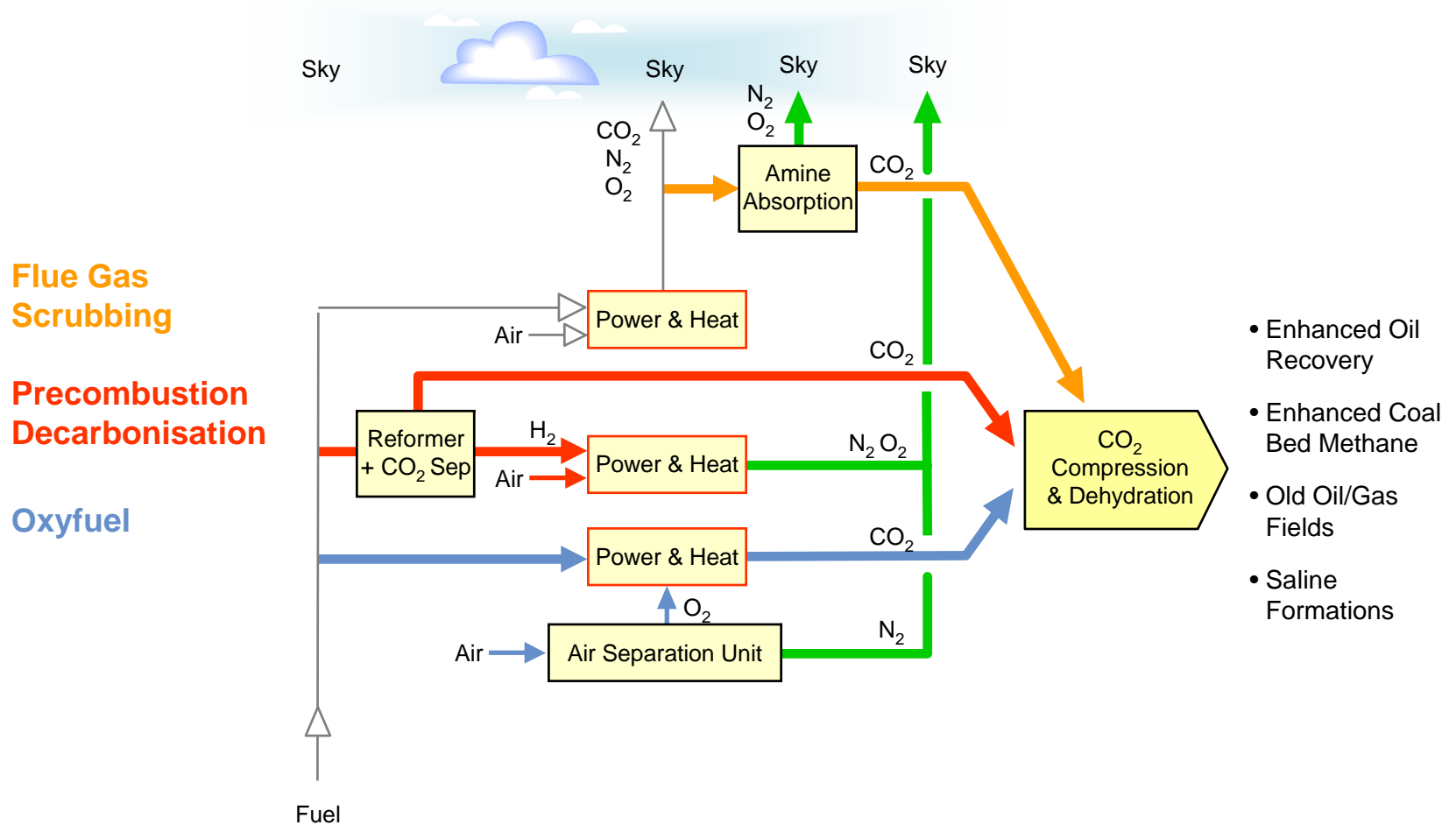
# Carbon Dioxide Management Reducing CO<sub>2</sub> Emissions



# Carbon Dioxide Management Reducing CO<sub>2</sub> Emissions



# Carbon Dioxide Management Reducing CO<sub>2</sub> Emissions



# CO<sub>2</sub> Separation Technologies

## Capabilities

	<u>Adsorption</u>	<u>Membrane</u>	<u>Absorption</u>	<u>Cryogenic</u>
<b>Feed Pressure</b>	Low to High	Medium to High	Low to High	Medium to High
<b>CO<sub>2</sub> Pressure</b>	Low	Low	Low	Low to Medium
<b>CO<sub>2</sub> Purity</b>	Medium to High	Low to Medium	Medium to High	High
<b>CO<sub>2</sub> Recovery</b>	Medium to High	Low	High	High

# CO<sub>2</sub> Separation Technologies

## Commercial Applications

Adsorption

Membrane

Absorption

Low Temp

Applications

Hydrogen  
Production

Natural Gas  
Purification

Syngas  
Purification

CO<sub>2</sub>  
Liquefaction

ASU Air  
Clean-up

Enhanced  
Oil Recovery

CO<sub>2</sub>  
Recovery  
from Flue  
Gas



# Flue Gas Scrubbing

- **Typical CO<sub>2</sub> Compositions...**

	<b>CO<sub>2</sub></b>	<b>Impurities</b>	<b>Pressure</b>
<b>Natural Gas Turbine Exhaust</b>	<b>3-4%</b>	<b>low SO<sub>x</sub> and NOx levels, 12-15% O<sub>2</sub></b>	<b>1 atm</b>
<b>Coal/Oil Fired Boilers</b>	<b>11-14%</b>	<b>high SO<sub>x</sub> and NOx levels, 2-5% O<sub>2</sub></b>	<b>1 atm</b>
<b>IGCC Syngas Turbine Exhaust</b>	<b>4.5-6%</b>	<b>Low SO<sub>x</sub> and NOx</b>	<b>1 atm</b>
<b>Blast Furnace Gas (after combustion)</b>	<b>25-30%</b>	<b>SO<sub>x</sub> and NOx present</b>	<b>1 atm</b>
<b>Cement Kiln off-gas</b>	<b>15-35%</b>	<b>Could have many impurities</b>	<b>1 atm</b>

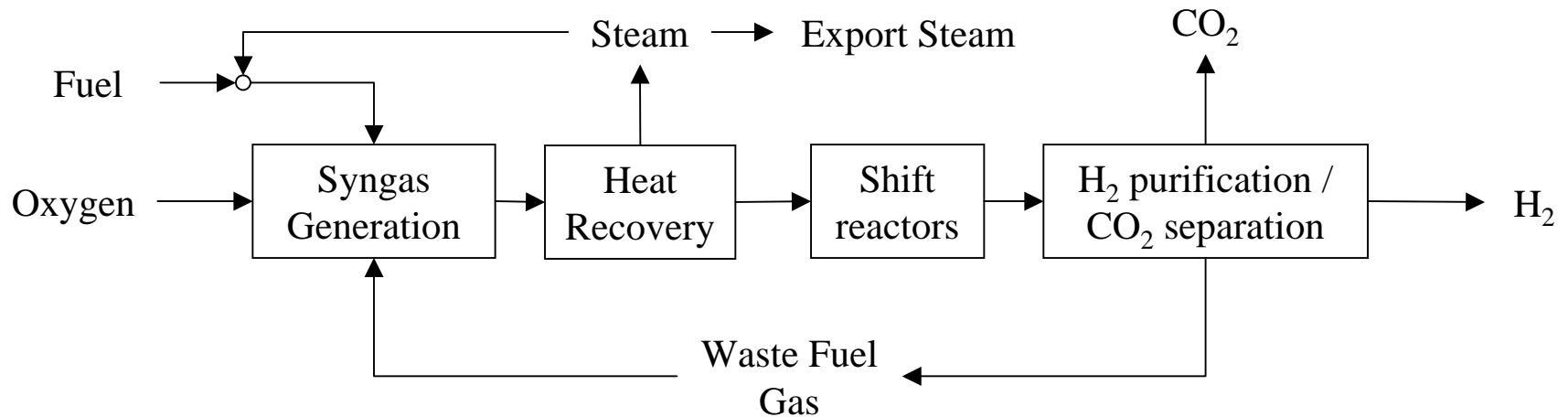
# Flue Gas Scrubbing

- **Uses aqueous amine solvents**
  - Sensitive to acidic impurities such as  $\text{NO}_2$ ,  $\text{SO}_2$ ,  $\text{SO}_3$  and  $\text{HCl}$
  - Pretreatment requirement to achieve low levels of  $\text{NO}_2$ ,  $\text{SO}_2$ ,  $\text{SO}_3$  and  $\text{HCl}$
- **Commercial systems available e.g.**
  - Kerr-McGee / ABB Lumus Crest
  - Fluor Daniel ECONAMINE
  - MHI
- **Utilities required**
  - Low pressure steam for regeneration
  - Power for pumping

# Flue Gas Scrubbing – Current Developments

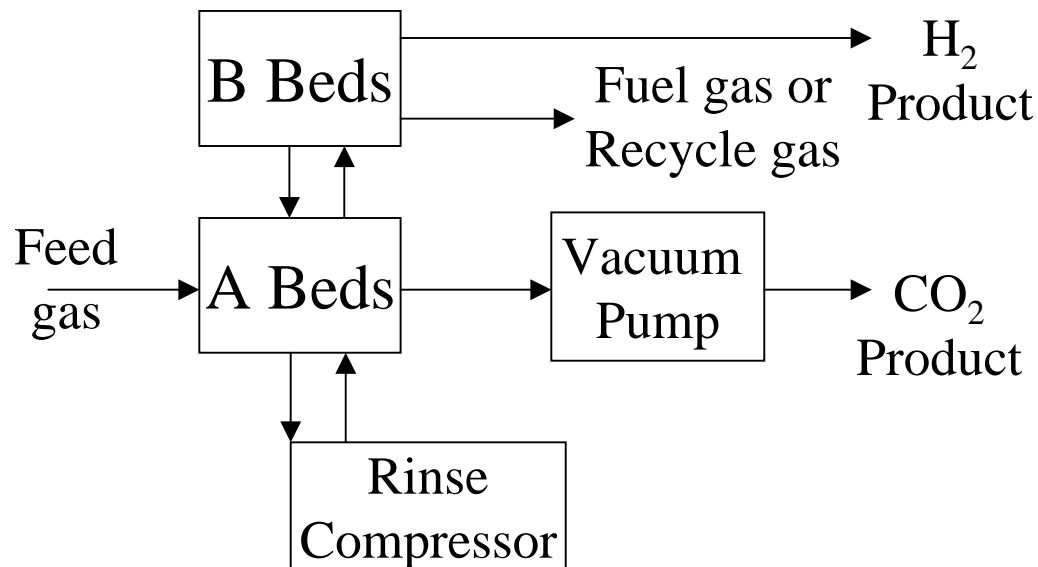
- **Advanced amine formulations**
  - **More resistant to acid gas impurities and oxygen**
  - **Lower regeneration energy**
- **New contacting devices**
  - **Hybrid membrane absorption systems**
- **High temperature regenerable solid sorbents**
  - **Lithium and Calcium Oxide based**

# General Arrangement For CO<sub>2</sub>-free Hydrogen Production



# Precombustion CO<sub>2</sub> Capture – Natural Gas Based Systems

- **Conventional hydrogen production**
  - SMR, POX, ATR
  - Convective Reforming Combined with the above
- **Conventional CO<sub>2</sub> removal**
  - Chemical or physical absorption system
  - Adsorption using a PSA system



- **Comparative economics at 42 MM SCFD H<sub>2</sub>(1986)**

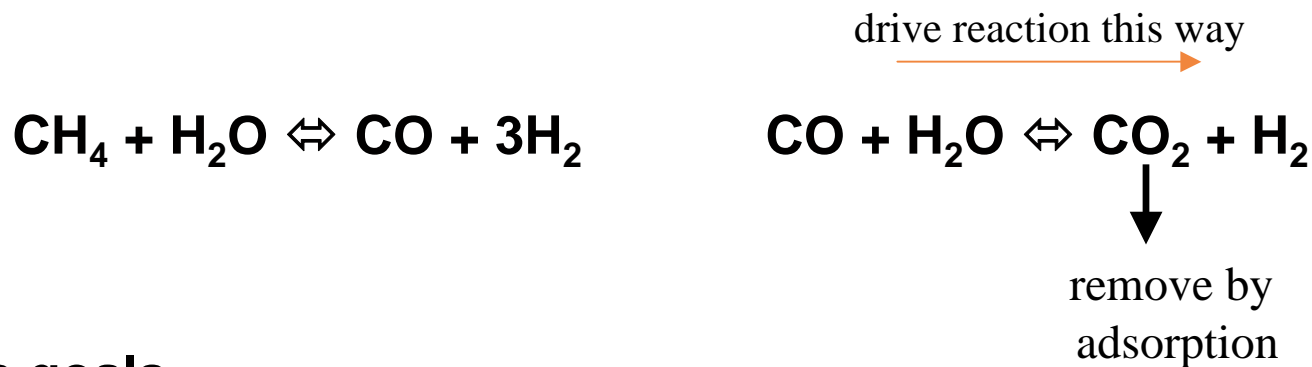
	<b>Gemini System</b>	<b>Amine /PSA</b>
<b>Capital (M\$)</b>	<b>9800</b>	<b>13300</b>
<b>Operating (M\$/yr)</b>	<b>550</b>	<b>590</b>



# Precombustion CO<sub>2</sub> Capture – Natural Gas Based Systems

## Concept

Combine reforming or water gas shift reaction with high temperature CO<sub>2</sub> removal to decarbonise gas turbine fuel

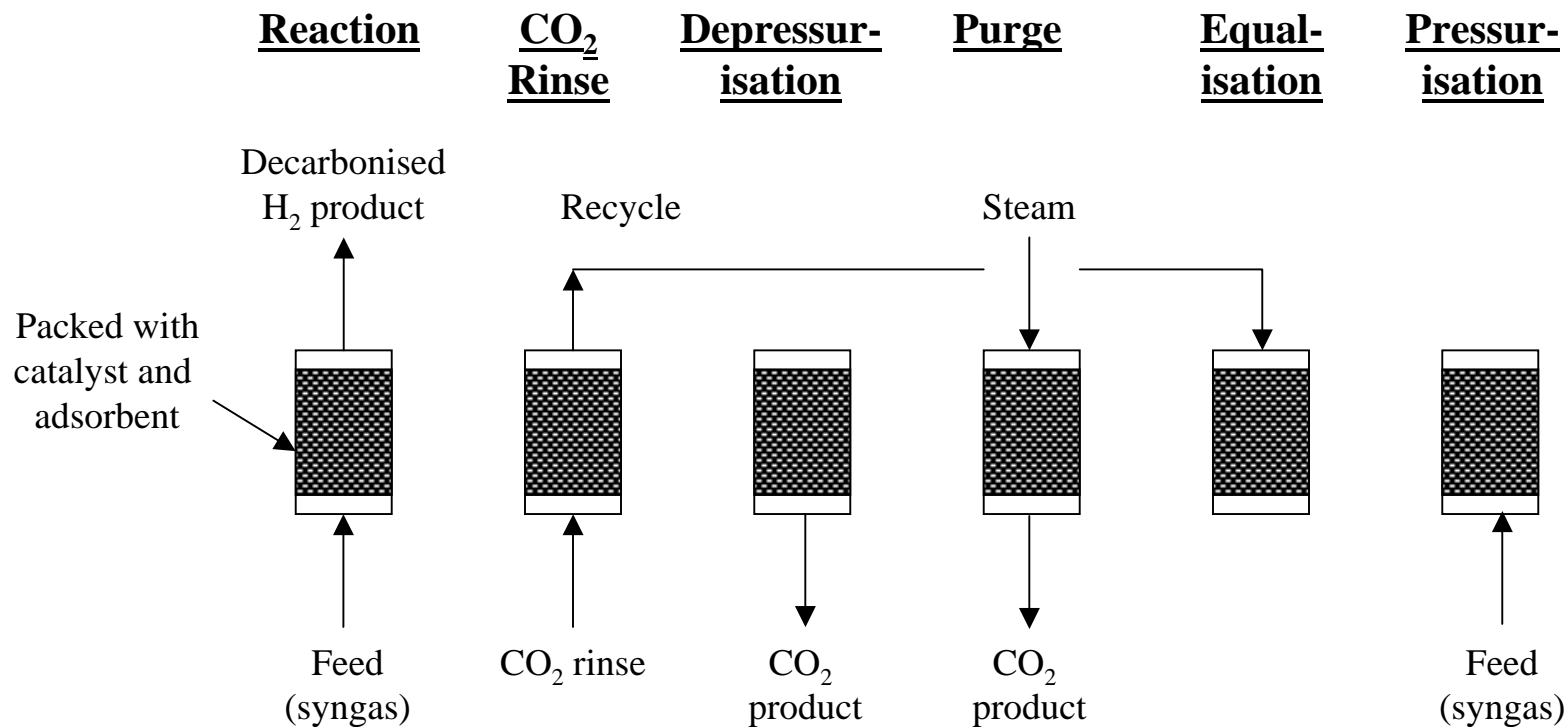


## Process goals

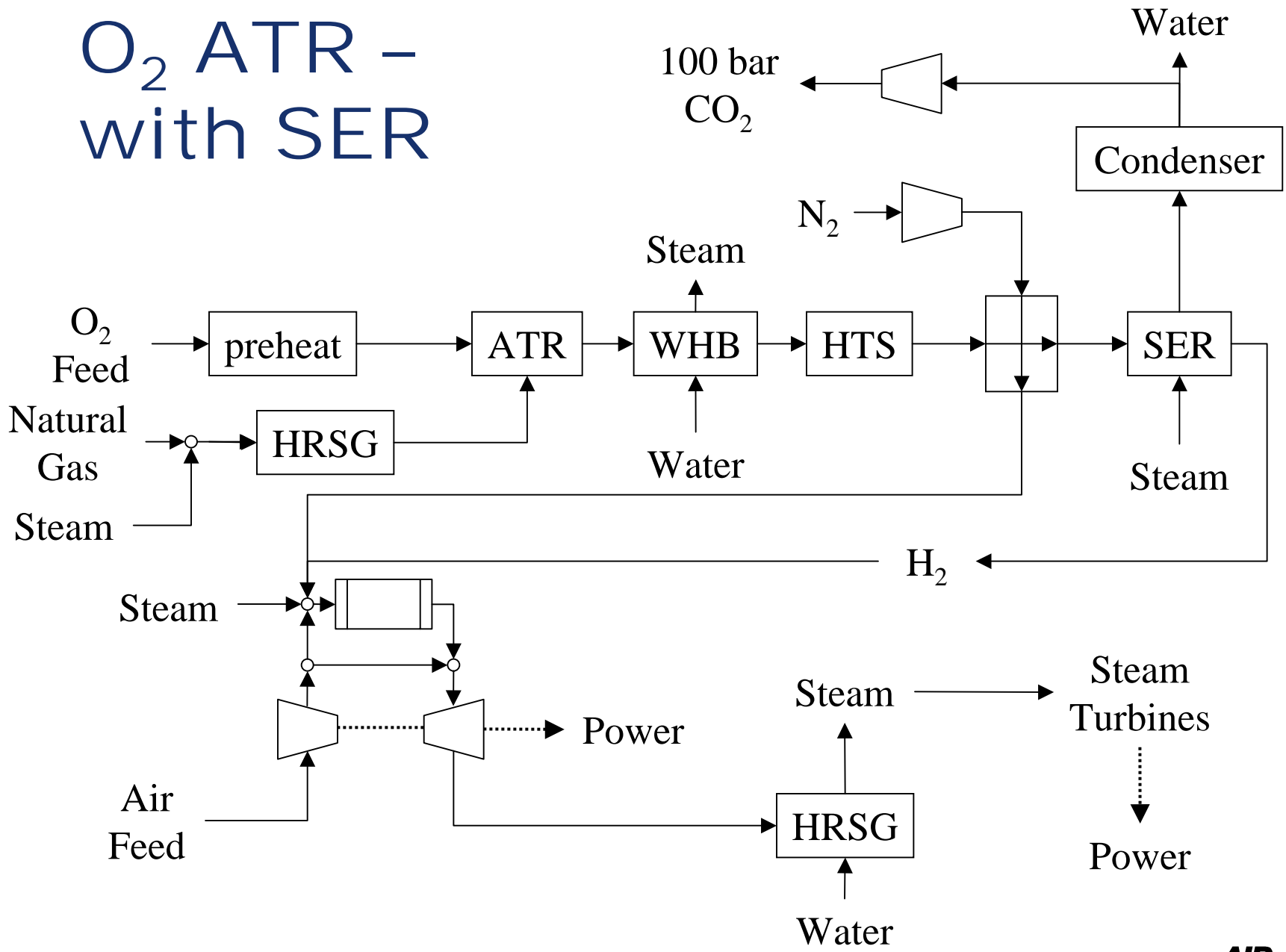
- Shift CO to low levels and simultaneously remove CO<sub>2</sub>
- Produce decarbonised H<sub>2</sub> fuel at high T/P
  - No steam condensation
  - Higher electrical generation efficiency

# A closer look at the SER process

- o Multiple adiabatic fixed beds containing mixture of shift catalyst and high temperature CO<sub>2</sub> adsorbent such as hydrotalcites
- o Cyclic operation, reaction step and regeneration steps
- o Regeneration by lowering pressure and purging with steam (Pressure Swing Adsorption, or PSA mode)
- o Specific process cycle developed to achieve 90+% carbon recovery, 97+% CO<sub>2</sub> purity, and 99+% H<sub>2</sub> recovery



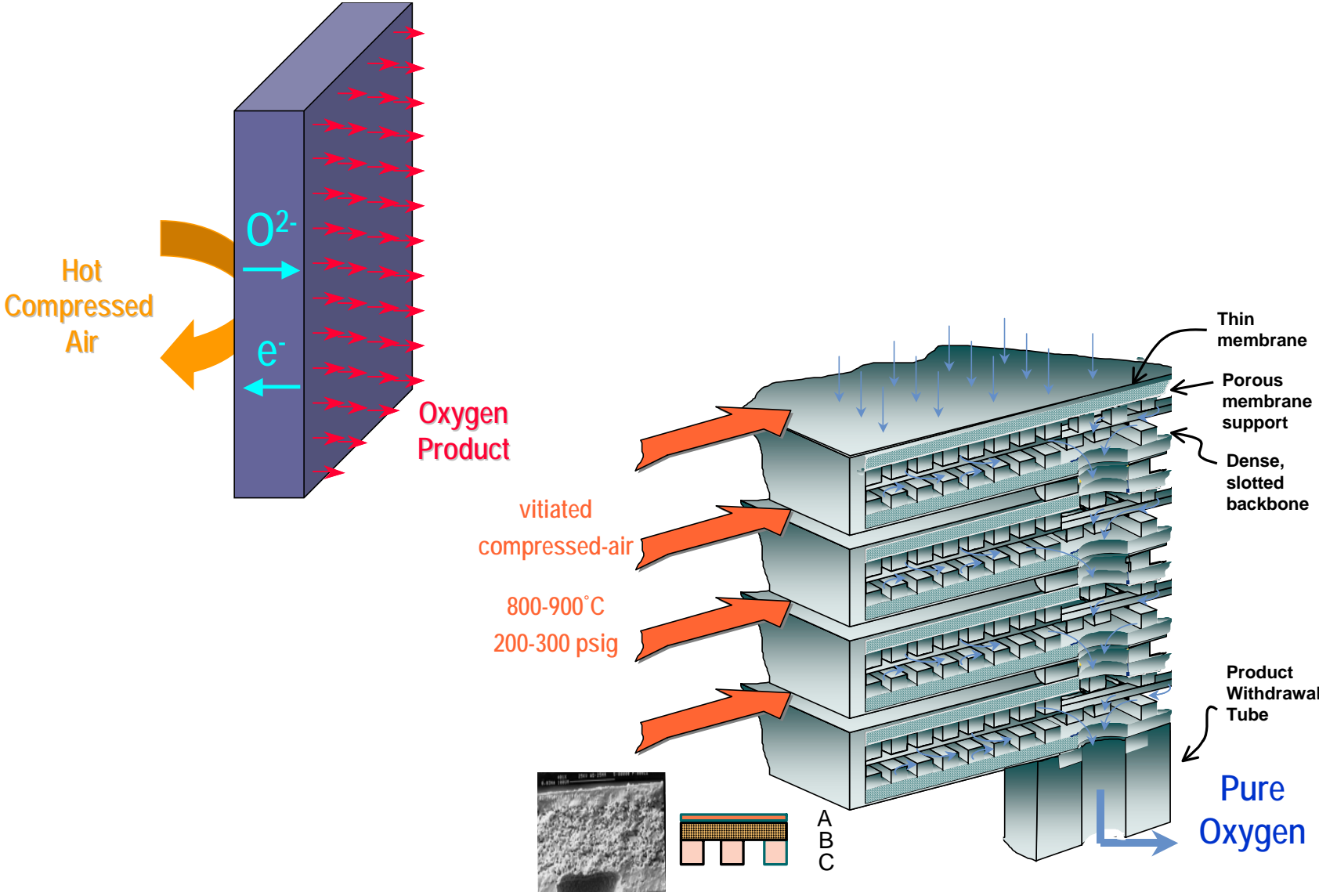
# O<sub>2</sub> ATR - with SER



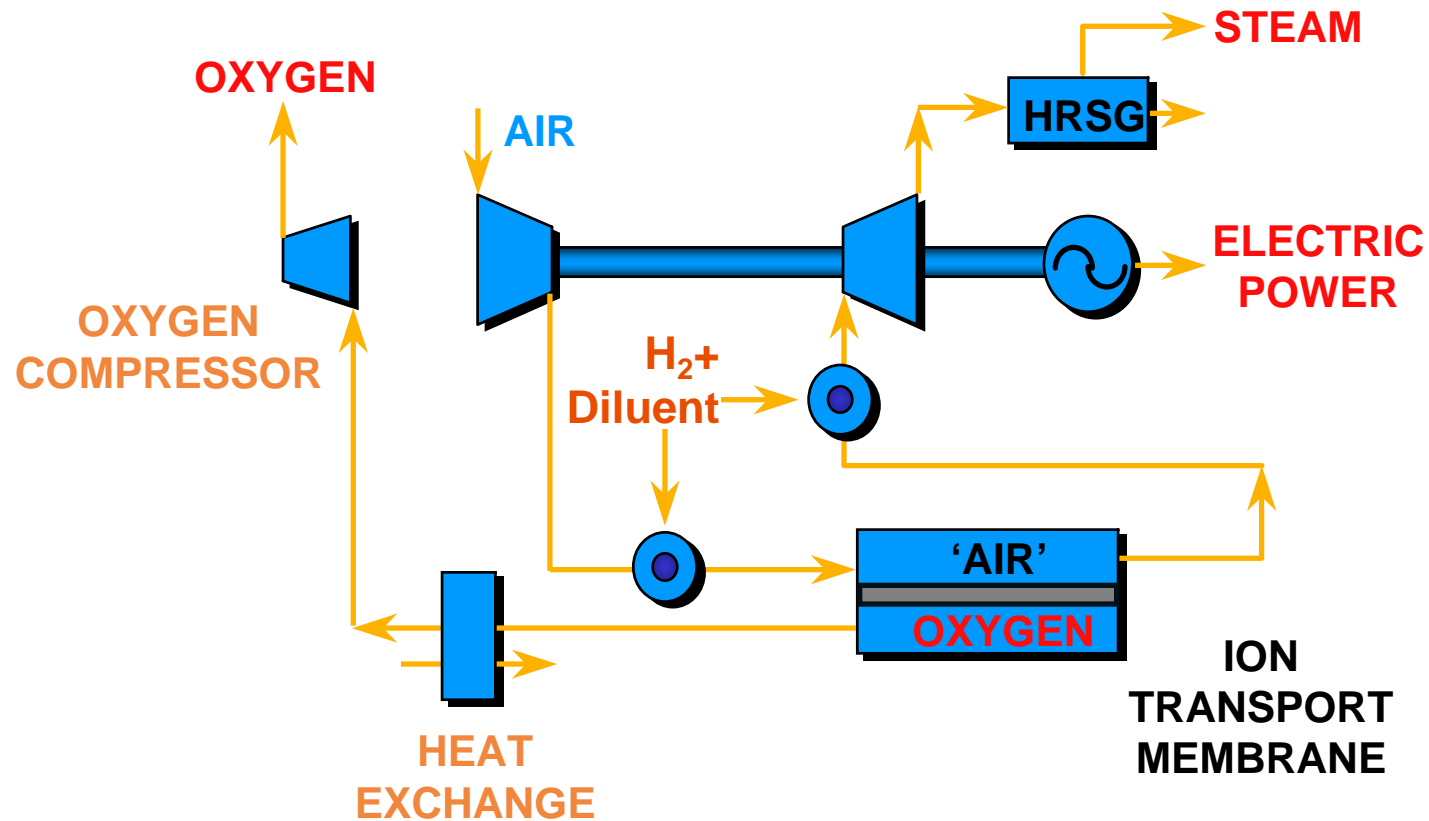
# Aspen simulation results with MDEA & SER systems

<b>MDEA</b>	<b>Air ATR</b>	<b>Air ATR SD</b>	<b>O<sub>2</sub> ATR</b>
<b>SER</b>			
<b>Carbon removal</b>	<b>94.2%</b> <b>99.3%</b>	<b>94.6%</b> <b>99.3%</b>	<b>96.2%</b> <b>97.9%</b>
<b>Efficiency</b>	<b>42.6%</b> <b>48.9%</b>	<b>41.8%</b> <b>46.6%</b>	<b>41.8%</b> <b>47.3%</b>
<b>\$/tonne CO<sub>2</sub></b>	<b>\$34.85</b> <b>-</b>	<b>-</b> <b>-</b>	<b>\$30.29</b> <b>\$24.02</b>

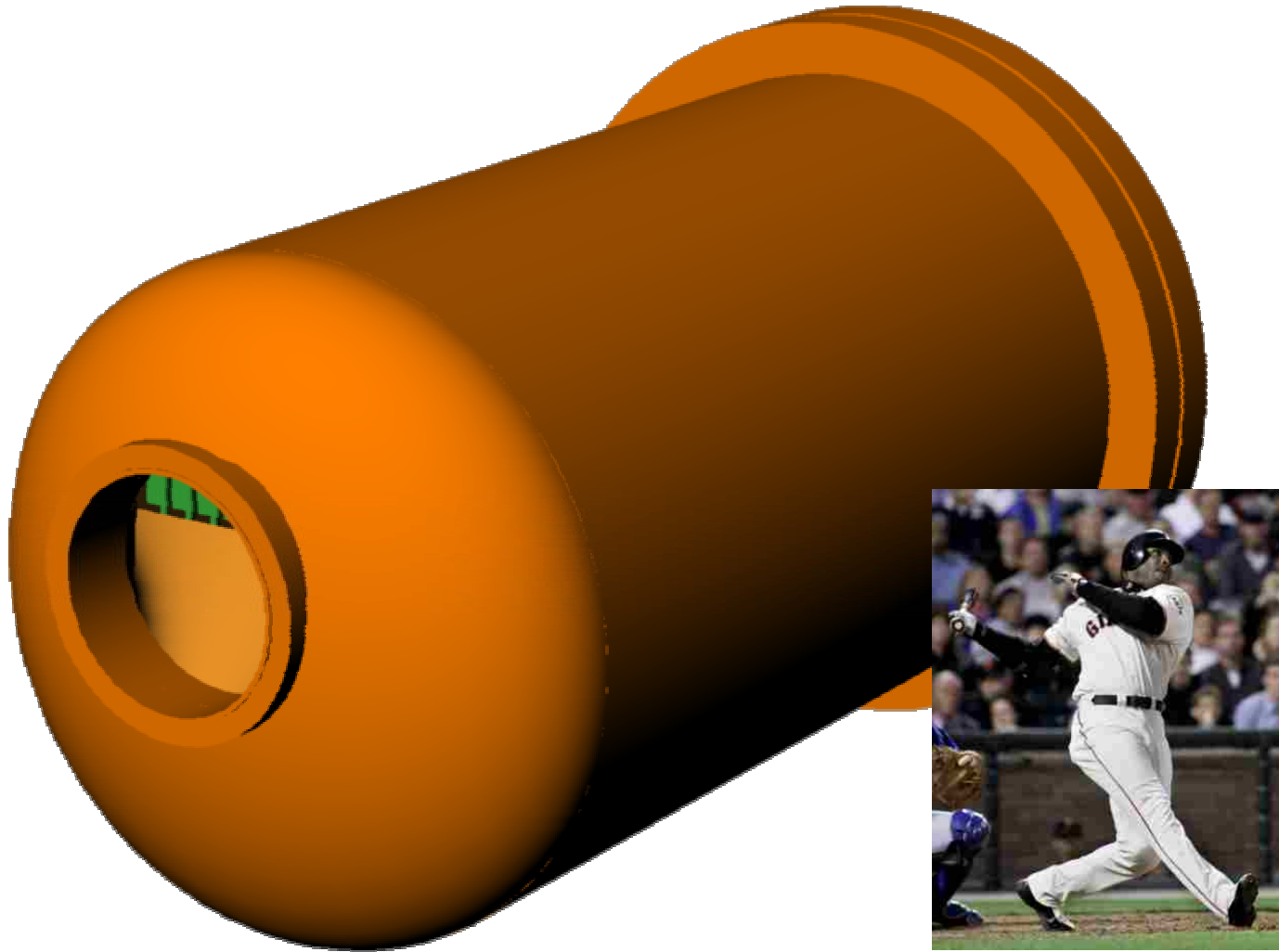
# Ion Transport Membrane



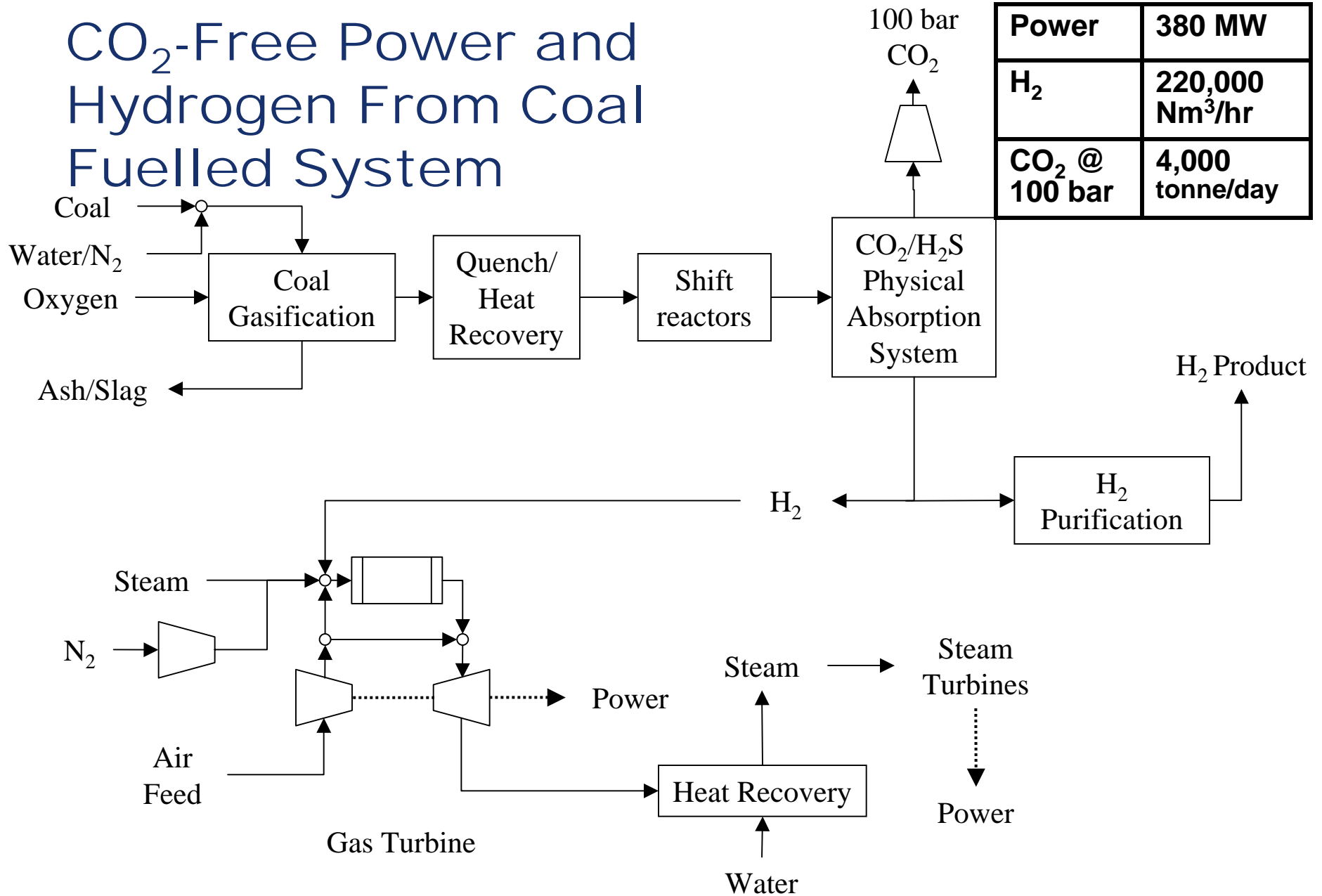
# Gas Turbine ITM Integration



# Commercial ITM Oxygen Vessel Concept: 350 tons/day



# CO<sub>2</sub>-Free Power and Hydrogen From Coal Fuelled System

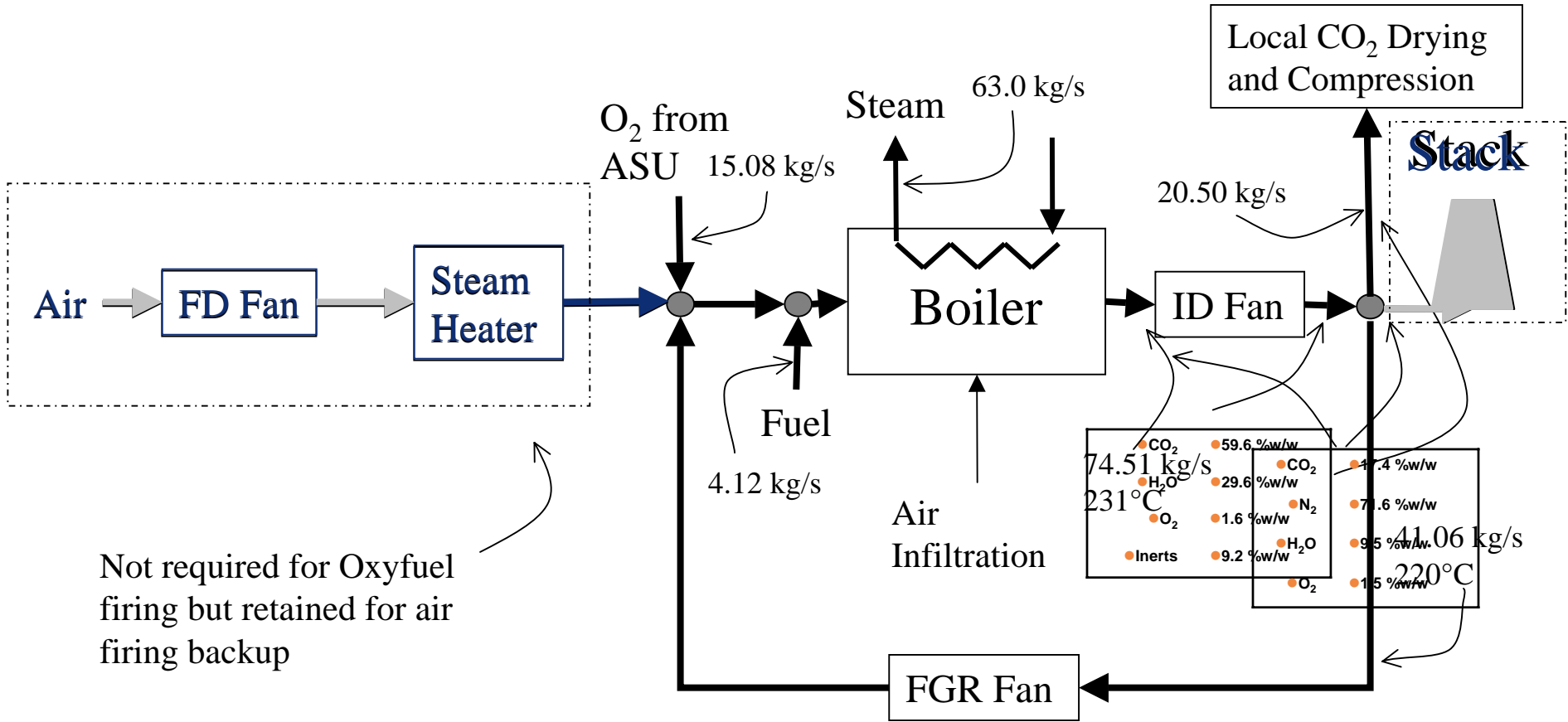


# Oxyfuel CO<sub>2</sub> Capture

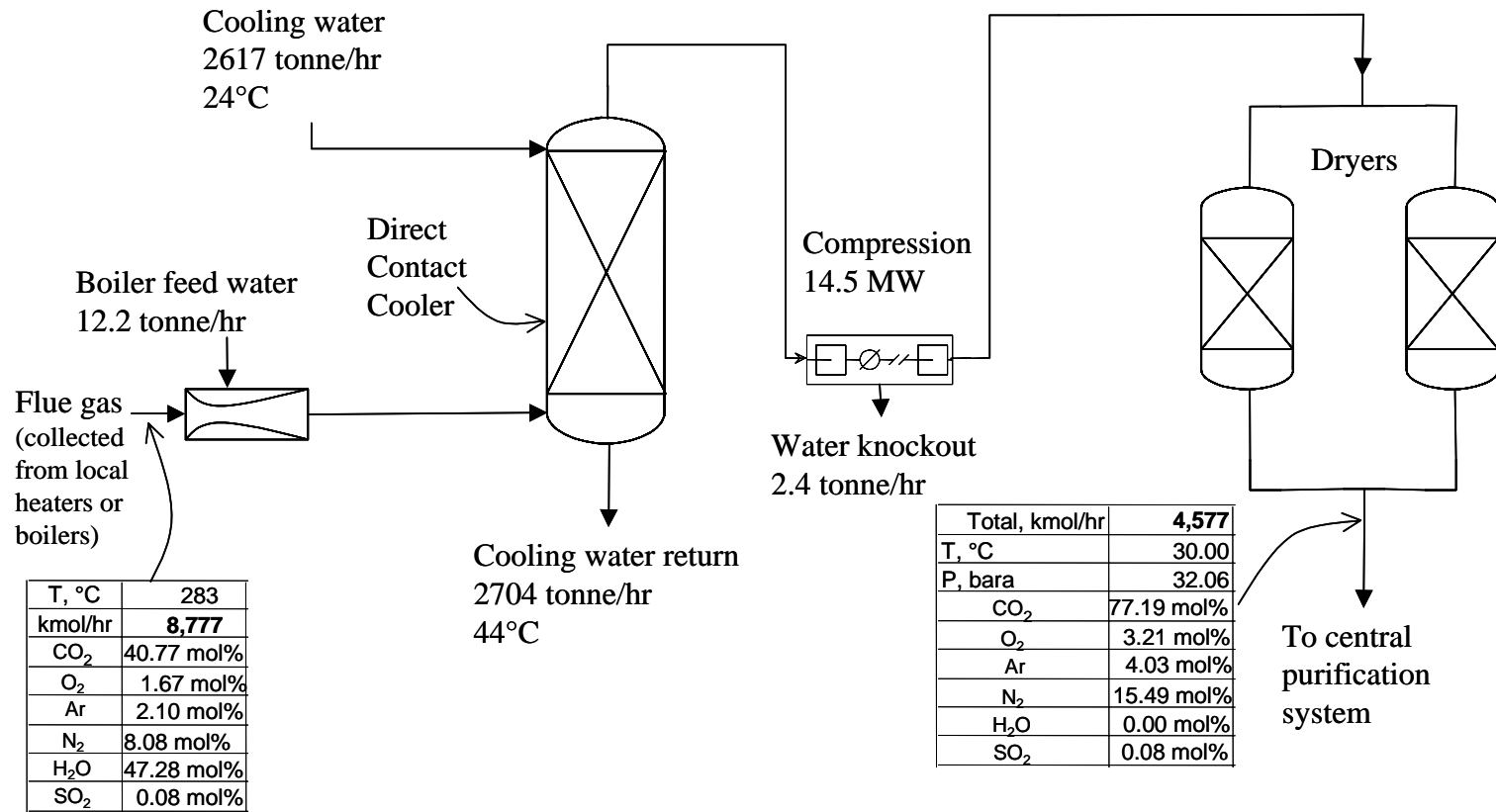
- **Eliminates N<sub>2</sub> from the flue gas by burning the fuel in oxygen**
- **Recycle of flue gas can be used to vary the flame temperature**
- **Combustion products contain:**
  - **CO<sub>2</sub> + H<sub>2</sub>O**
  - **Any inerts from air inleakage or oxygen impurities**
  - **Oxidation products and impurities from the fuel (SO<sub>x</sub>, NO<sub>x</sub>, HCl, Hg, etc.)**

# Oxyfuel Boiler Conversion

(CCP Grangemouth System)

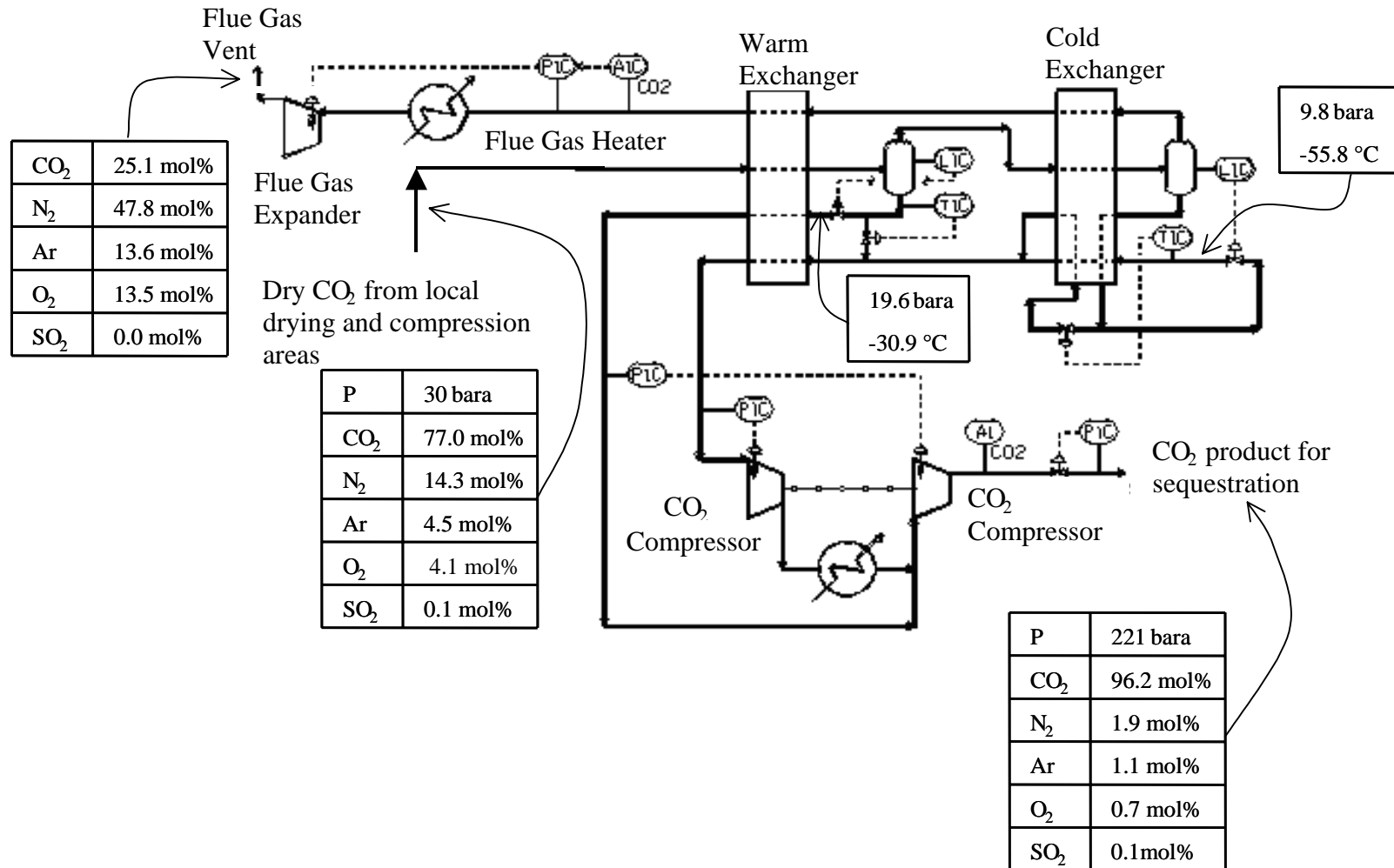


# Raw CO<sub>2</sub> Treatment

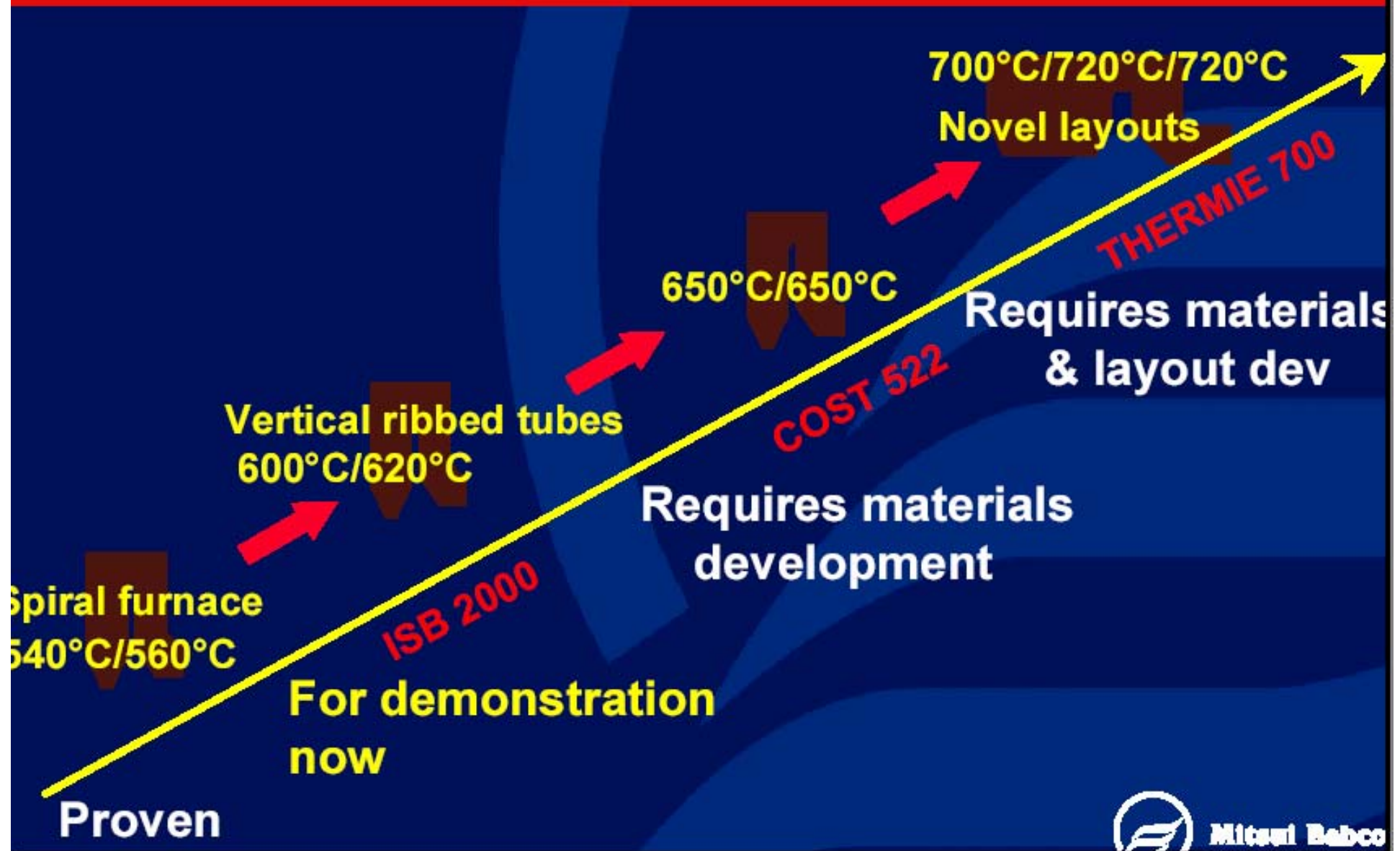


# Central CO<sub>2</sub> Purification and Compression System

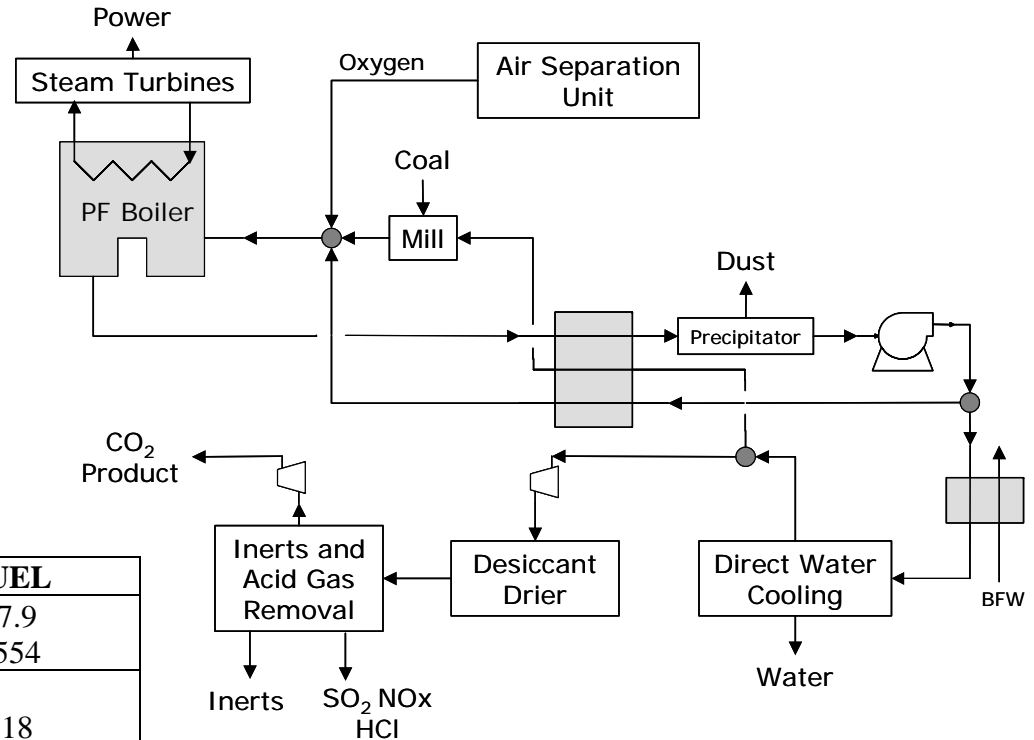
(CCP Grangemouth System)



# Progression of Supercritical PF



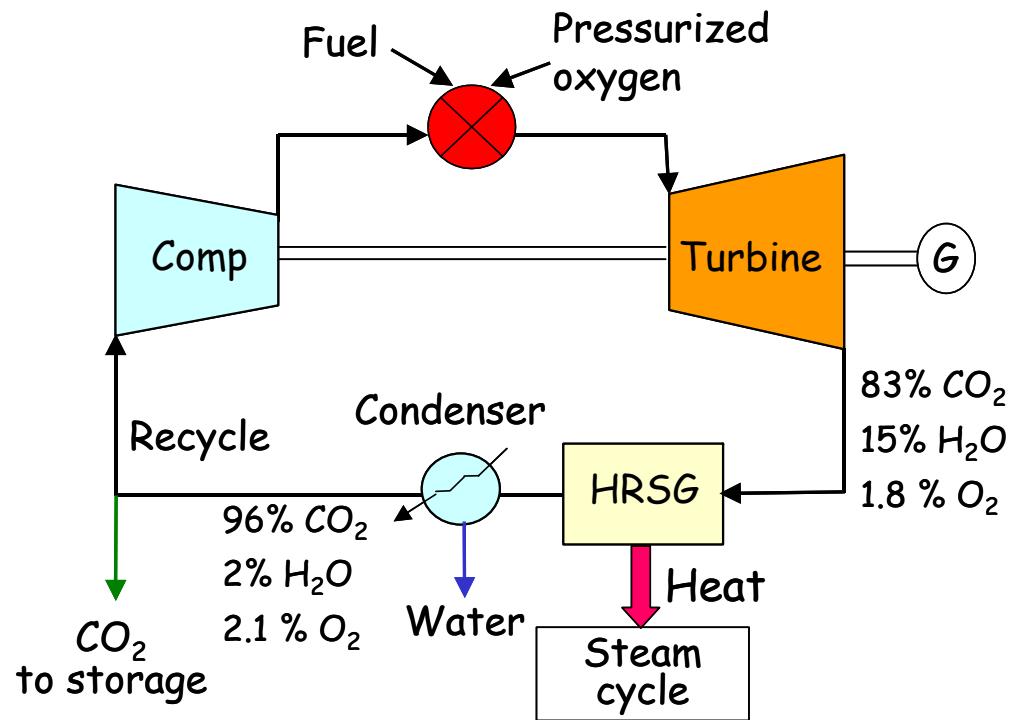
# Oxyfuel PF Coal Fired Power Station



	AIR	OXYFUEL
Coal flow kg/sec (dry ash free)	47.9	47.9
Heating value MW(LHV)	1554	1554
Power		
Steam turbines MW	652	718
Auxiliaries MW	-26	-28
Oxygen plant MW	-	-103
CO <sub>2</sub> compression MW	-	-76.5
Total net power MW	626	511
Net efficiency %	40.3	32.9
Oxygen		
Flow tonne/day	0	11000
Purity %	-	95
CO <sub>2</sub>		
Flow tonne/h	0	480
Pressure bara	-	220
Purity %	-	99.99
Recovery %	-	91.3

- **Cryogenic Air Separation Unit uses adiabatic air compressor**
- **CO<sub>2</sub> compressor has two adiabatic stages**
- **Heat for condensate and boiler feedwater preheating**
- **Supercritical and Oxyfuel are suitable for retro-fit or new build**
- **Supercritical/Oxyfuel efficiency ~38% (approximately the same as IGCC)**

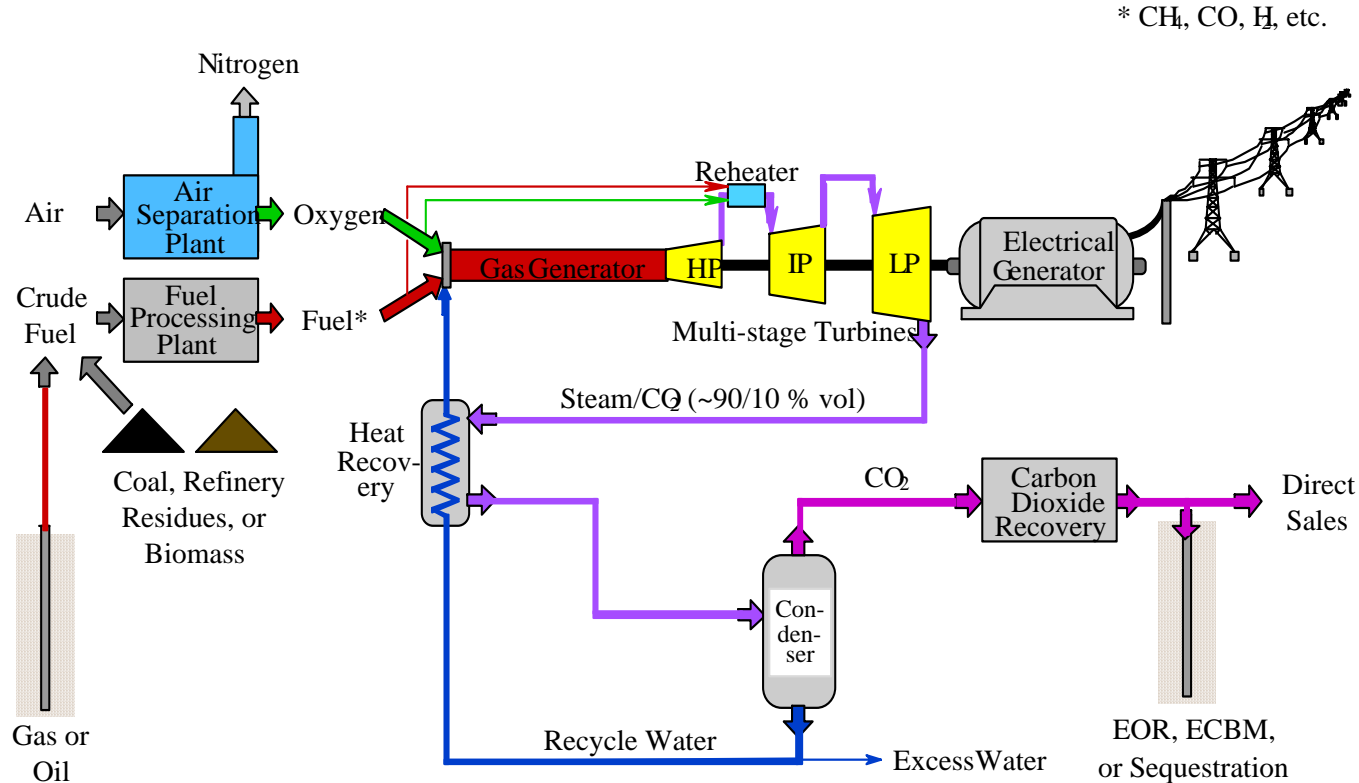
# Natural Gas Fired Oxyfuel Gas Turbine Combined Cycle



<b>Net Power</b>	<b>226 MW</b>
<b>Efficiency</b>	<b>~45% LHV</b>
<b>Oxygen</b>	<b>3400 tonne/day</b>

# A Water Quenched Direct Fuel Oxygen Combustion (CES Cycle)

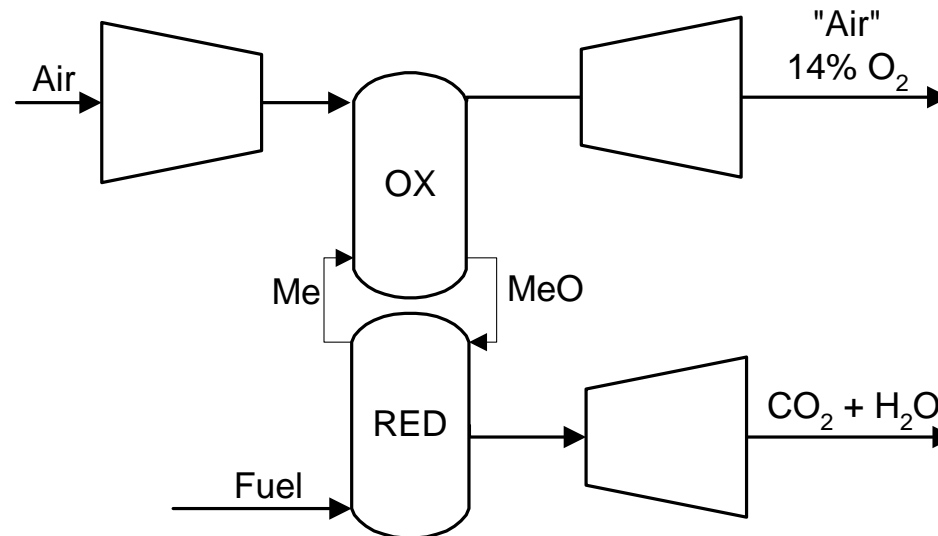
- No limit on steam temperature
- Efficiencies >50% possible



# The Chemical Looping Combustion Principle

- Metal oxides of transition metals
- Reactor Temperatures 800-1200°C
- Either Brayton or Rankine steam cycle

No oxygen plant required



Thank you

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