

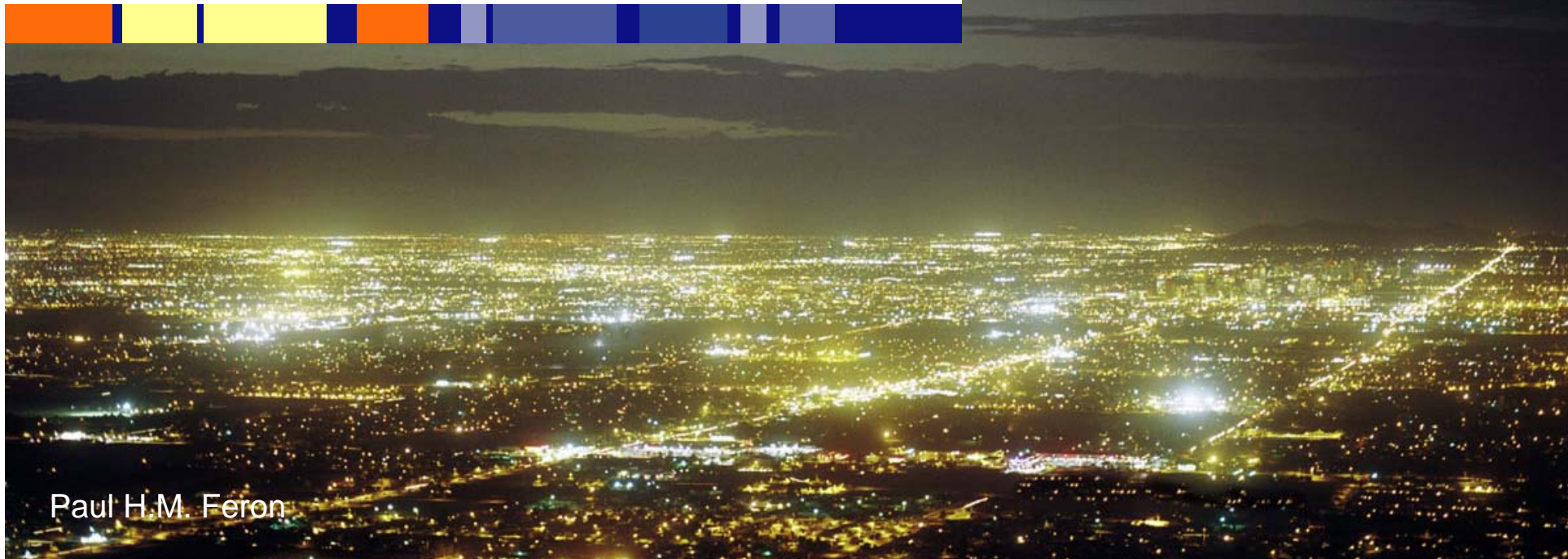
# Progress in post-combustion CO<sub>2</sub> capture

1<sup>st</sup> Regional Carbon management symposium,  
Dhahran, Saudi Arabia, 23 May 2006

**TNO | Knowledge for business**



Paul H.M. Feron



# Presentation Overview

- ❑ CO<sub>2</sub> capture introduction
- ❑ Post-combustion capture: State of the art
  - Solvent technologies
  - Performances
  - Issues
- ❑ Post-combustion capture: Advanced processes
- ❑ Conclusions



# CO<sub>2</sub> capture introduction



# What are challenges for CO<sub>2</sub> capture?

Capture of CO<sub>2</sub> can be done with technologies presently available but:

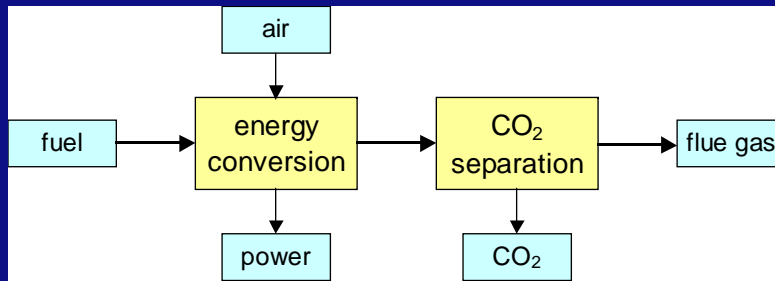
- Sizeable efficiency reduction
- Power generation costs will increase
- There is no experience with CO<sub>2</sub> capture at the power plant scale

Therefore the following questions need to be addressed:

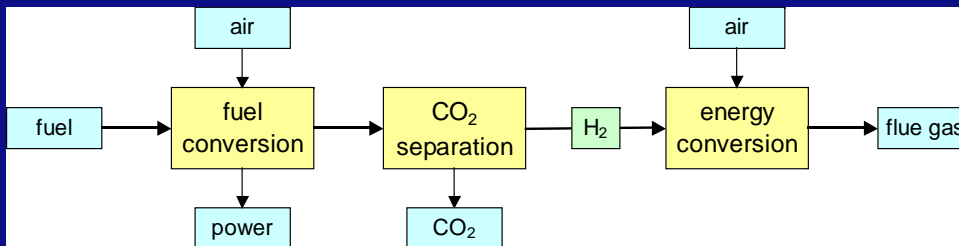
- How to reduce the additional power consumption as a result of the capture process?
- How to reduce the costs of the capture?
- Are these processes reliable?



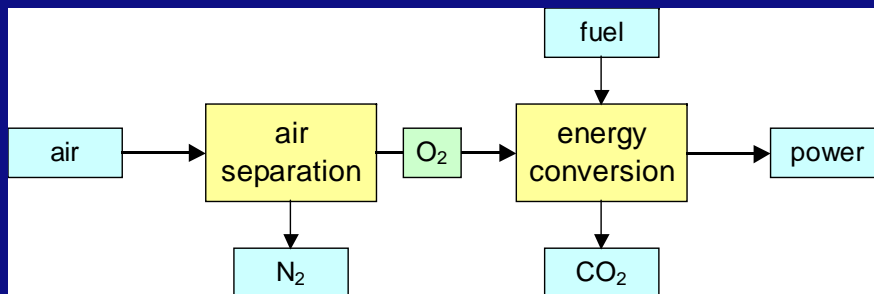
# Decarbonisation routes for power plants



Post-combustion



Pre-combustion



Denitrogenation

# CO<sub>2</sub>-capture classification

## By process:

- Post-combustion decarbonisation  
(conventional power plants)
- Pre-combustion decarbonisation  
(new power plants)
- Denitrogenation  
(new power plants)

## By technology platform/component:

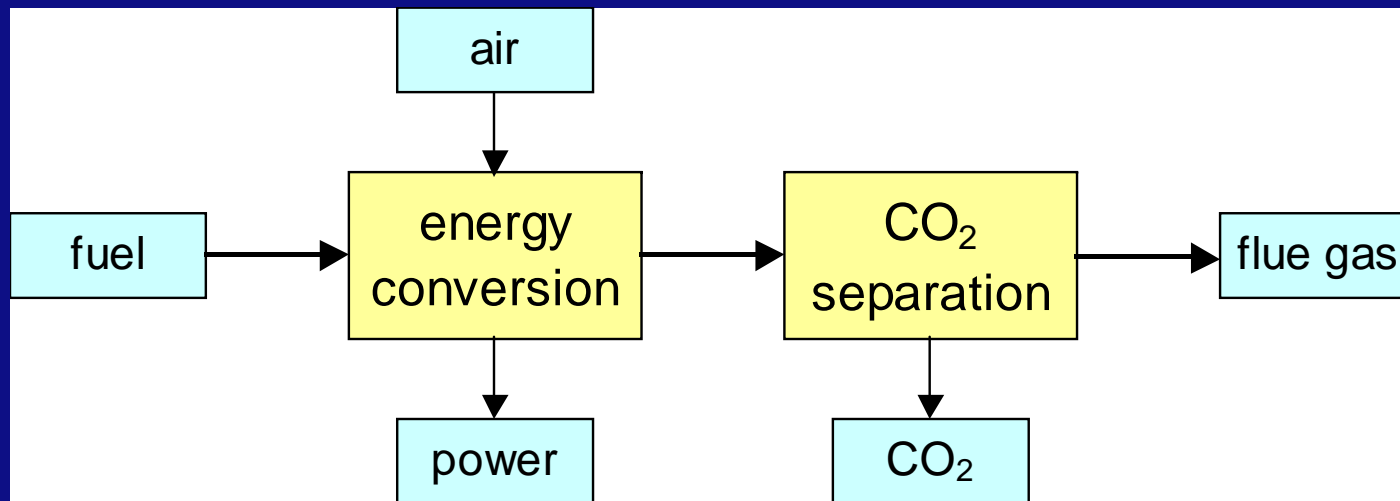
- Membranes
- Absorption
- Adsorption
- Cryogenics
- Carbon extraction
- Biotechnology
- Energy conversion



# The CO<sub>2</sub> Capture toolkit: A portfolio approach

Capture method	Post-combustion processes	Pre-combustion processes	Denitrogenation
<b>Solvents</b>	<b>New solvents Contactors Process design</b>	<b>New solvents Contactors Process design</b>	<b>O<sub>2</sub>/N<sub>2</sub> absorbent</b>
<b>Membranes</b>	<b>Membrane absorption, polymeric, ceramic, FT, carbon membranes</b>	<b>CO<sub>2</sub>/H<sub>2</sub>-separation: Ceramic, polymeric, palladium, membrane absorption</b>	<b>O<sub>2</sub>-conducting membranes</b>
<b>Sorbents</b>	<b>Lime carbonation</b>	<b>Dolomite Zirconates</b>	<b>O<sub>2</sub>/N<sub>2</sub> adsorbents High T adsorbents</b>
<b>Cryogenic</b>	<b>Liquefaction</b>	<b>CO<sub>2</sub>/H<sub>2</sub> separations</b>	<b>Distillation for air separation</b>
<b>Carbon extraction</b>	<b>n.a.</b>	<b>Direct decarbonisation</b>	<b>n.a.</b>
<b>Biotechnology</b>	<b>Algae production Biomimetic approaches</b>	<b>High pressure applications</b>	<b>Biomimetic approaches</b>
<b>E-Conversion</b>	<b>Novel power cycles</b>	<b>Hydrogen combustion</b>	<b>Combustion in O<sub>2</sub>/CO<sub>2</sub>/H<sub>2</sub>O atmosphere</b>

# Post-combustion CO<sub>2</sub> capture CO<sub>2</sub>-removal from flue gases



# Why post-combustion capture?

- ❑ Add-on to existing power plants and plant concepts
- ❑ Capture technologies available, i.e. solvent technologies, which are proven on a smaller scale
- ❑ Similarities with cogeneration plant lead to proven methods for integration
- ❑ Capture readiness easy to incorporate into power plant tackling issue with infrastructure inertia
- ❑ Flexibility in switching between capture – no capture
- ❑ Learning by doing will lead to cost reductions similar to experience with SO<sub>2</sub> capture process development
- ❑ Learning by searching will lead to better solvents and processes

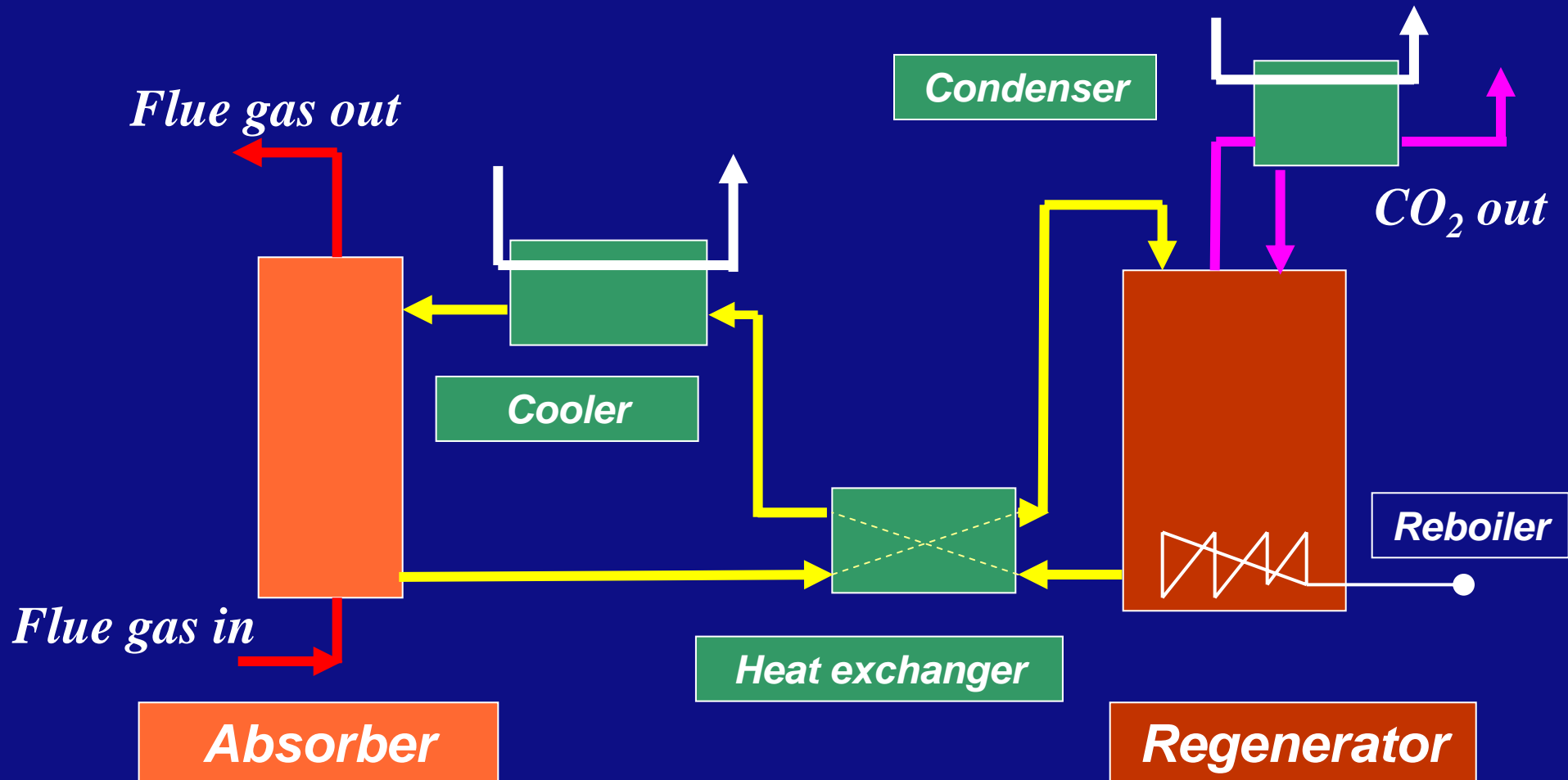


# Post-combustion capture: State of the art



# Solvent process flow sheet

## Aqueous ethanolamine solutions



# State of the art post-combustion CO<sub>2</sub>-capture

- ❑ Fluor Daniel Econamine FG<sup>SM</sup>
  - 30% MEA solution incorporating additives to control corrosion
  - > 20 commercial plants in sizes between 0.2 and 15 tonnes CO<sub>2</sub>/h
- ❑ ABB-Lummus
  - 15-20% MEA solution
  - 4 commercial plants in size between 6 and 32 tonnes CO<sub>2</sub>/h
- ❑ Mitsubishi Heavy Industries
  - KS-1 – sterically hindered amines
  - 1 commercial plant: 9 tonne CO<sub>2</sub>/h
- ❑ More to come.....



# Overview of consequences for European power plants

## CASTOR Results

Item	Increase in investment	CoE Increase	Efficiency decrease	Cost per tonne CO <sub>2</sub> avoided
Gas fired combined cycle [393 MW <sub>e</sub> ]	48 %	51 %	18 %	54 €
Bituminous coal fired power plant [600 MW <sub>e</sub> ]	25 %	84 %	31 %	40 €
Lignite fired power plant [1000 MW <sub>e</sub> ]	17 %	88 %	34 %	40 €



## Contributions to increase in CoE CASTOR results

- CoE increases due to decreased power output
- CoE increases due additional investments

Power plant	CoE increase due to capital costs	CoE increase due to efficiency loss
GTCC	60 %	40 %
Solid fuel power plants	40 %	60 %

# Equipment costs contributions CASTOR results

	Gas fired combined cycle	Bituminous coal fired power plant
<b>Absorber</b>	57 %	45 %
<b>Blower</b>	16 %	14 %
<b>Stripper</b>	7 %	16 %
<b>Pumps</b>	7 %	15 %
<b>Rest</b>	13 %	10 %
<b>Total</b>	100 %	100 %



# Issues for post-combustion CO<sub>2</sub>-capture

- ❑ Solvent technologies are leading option but currently:
  - Power cost increases >50%
  - Generation efficiency decreases by 15 – 35%
  
- ❑ Solvent process break-throughs required
  - Energy requirements
  - Reaction rates
  - Contactor improvements
  - Liquid capacities
  - Chemical stability/corrosion
  - Desorption process improvements
  - Hence cost reductions
  
- ❑ Integration with power plant
  - Heat integration with other process plant, particularly in relation to desorption process
  - Concepts for “capture readiness”



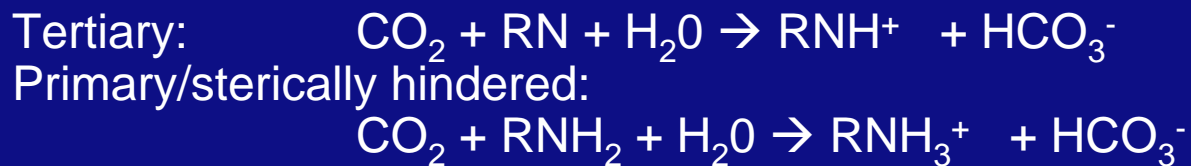
# Ethanolamine reaction chemistry: General

## □ Primary, secondary amines (MEA, DEA)



- A carbamate with varying degrees of stability is formed
- Fast reaction kinetics
- Max. loading: 0.5 mol/mol amine

## □ Tertiary amines, sterically hindered amines (TEA, MDEA, AMP)



- Formation of bicarbonate in presence of water
- Slow reaction kinetics
- Max. loading: 1.0 mol/mol amine



# Energy impacts for post-combustion CO<sub>2</sub> capture using solvent processes

## □ Thermal energy

- Regeneration of solvents; Extracted from steam cycle in power plant:
  - Sum of solvent heating, desorption enthalpy and reflux ratio
  - Energy impact determined by solvent properties, process design and integration into power plant

## □ Electricity

- Flue gas fans:
  - Higher CO<sub>2</sub>-content in flue gas reduces specific power consumption
- Solvent pumps, cooling water pumps:
  - Higher CO<sub>2</sub>-loading of solvent reduces specific power consumption
- CO<sub>2</sub> compressor:
  - Specific power consumption determined by pressure ratio



# Post-combustion capture process performances: Past, present and future

Year	1995	2005	2015
Thermal energy	4.2 GJ/tonne CO <sub>2</sub>	3.2 GJ/tonne CO <sub>2</sub>	2.0 GJ/tonne CO <sub>2</sub>
Power equivalent (Factor used)	0.292 kWh/kg CO <sub>2</sub> (0.25)	0.178 kWh/kg CO <sub>2</sub> (0.20)	0.083 kWh/kg CO <sub>2</sub> (0.15)
Power for capture	0.040 kWh/kg CO <sub>2</sub>	0.020 kWh/kg CO <sub>2</sub>	0.010 kWh/kg CO <sub>2</sub>
CO <sub>2</sub> compressor	0.114 kWh/kg CO <sub>2</sub>	0.108 kWh/kg CO <sub>2</sub>	0.103 kWh/kg CO <sub>2</sub>
Total	0.446 kWh/kg CO <sub>2</sub>	0.306 kWh/kg CO <sub>2</sub>	0.196 kWh/kg CO <sub>2</sub>

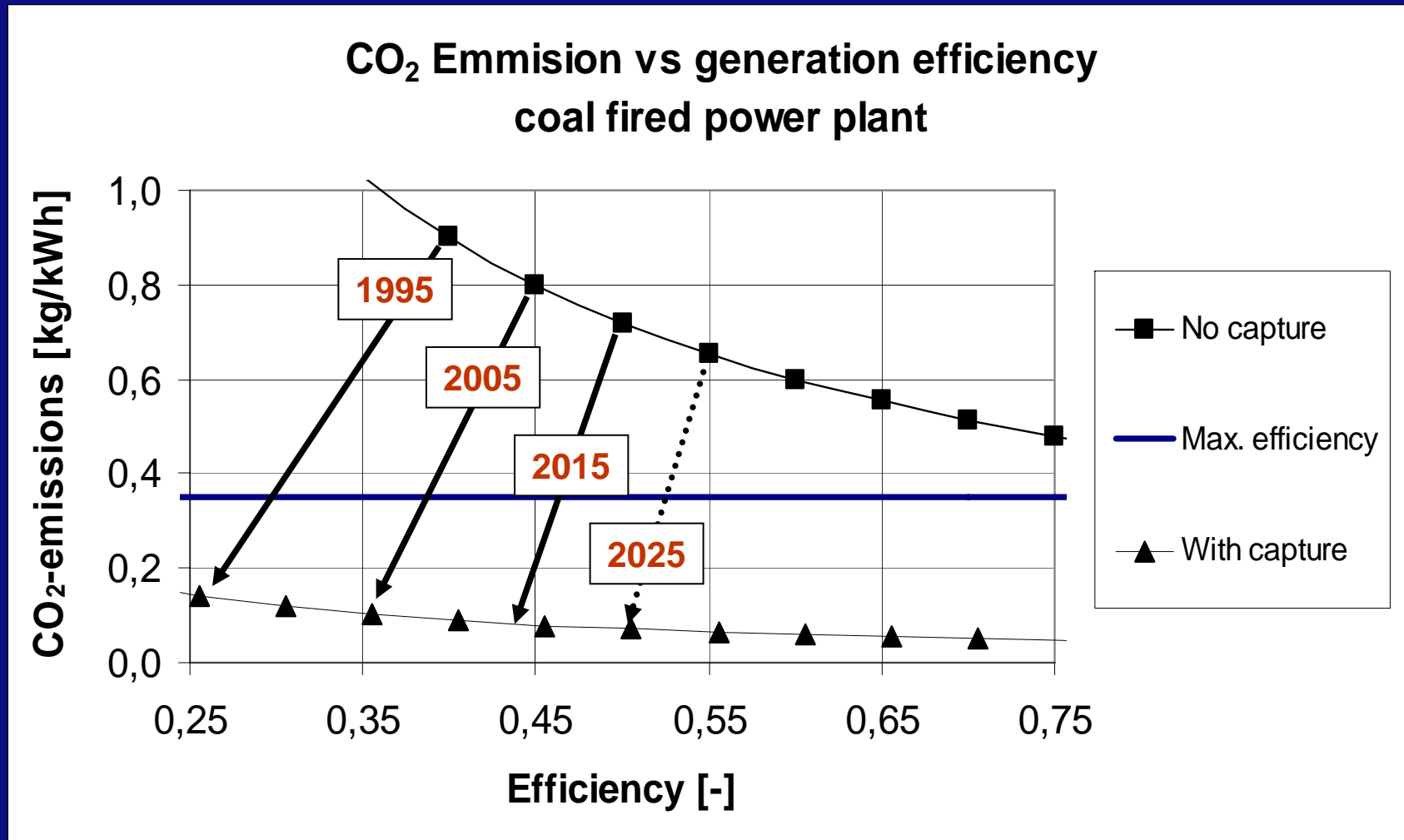


# Post-combustion capture in a coal fired power plant (Emission factor: 0.1 tonne CO<sub>2</sub>/GJ)

Year	1995	2005	2015
Base plant efficiency	40 %	45 %	50 %
Base plant emission	900 kg CO <sub>2</sub> /MWh	800 kg CO <sub>2</sub> /MWh	720 kg CO <sub>2</sub> /MWh
Power loss due to capture	0.446 kWh/kg CO <sub>2</sub>	0.306 kWh/kg CO <sub>2</sub>	0.196 kWh/kg CO <sub>2</sub>
Plant efficiency with 90% capture	25.5 %	35.1 %	43.6 %
Emission with 90% capture	141 kg CO <sub>2</sub> /MWh	103 kg CO <sub>2</sub> /MWh	82 kg CO <sub>2</sub> /MWh



# Development of capture technology hand in hand with generation efficiency improvements



# Research and Development trends

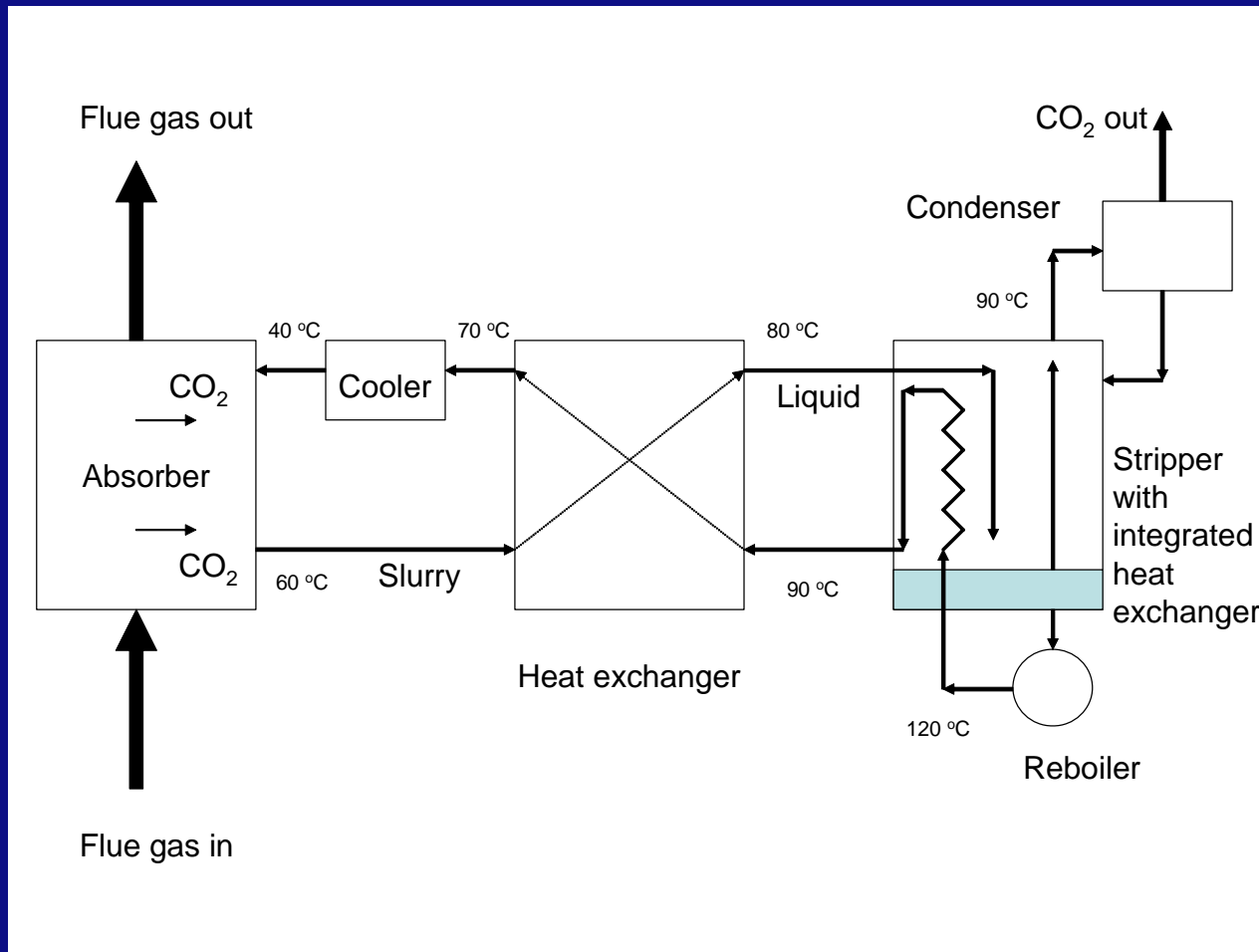
- ❑ Formulated amines
  - Mixtures of “promoters and loaders”
  - Corrosion inhibitors added
- ❑ Multiple amine groups
  - Diamines, triamines
  - Hyperbranched polymers
- ❑ Non-aqueous solvents
  - Ionic liquids
- ❑ Modified process concepts
  - Intercooling
  - Heat exchange integration in stripper
  - Integration of compression
  - Split flow
- ❑ Novel process components
  - Membrane contactors
- ❑ Robust solvents
  - Ammonia



# Post-combustion capture: Advanced processes



# DECAB process flow diagram (amino-acid salts)



**Precipitation the absorber will result in high loading of the solvent and hence reduction of costs**

# Technical comparison for pulverised coal fired power station (90% CO<sub>2</sub> removal)

	MEA	DECAB
Thermal energy [GJ/tonne CO <sub>2</sub> ]	4.2	2.3
Electricity [kWh/tonne CO <sub>2</sub> ]	69	41
Cooling water [m <sup>3</sup> /tonne CO <sub>2</sub> ]	73	37
Chemicals [kg/tonne CO <sub>2</sub> ]	1.0	0.1

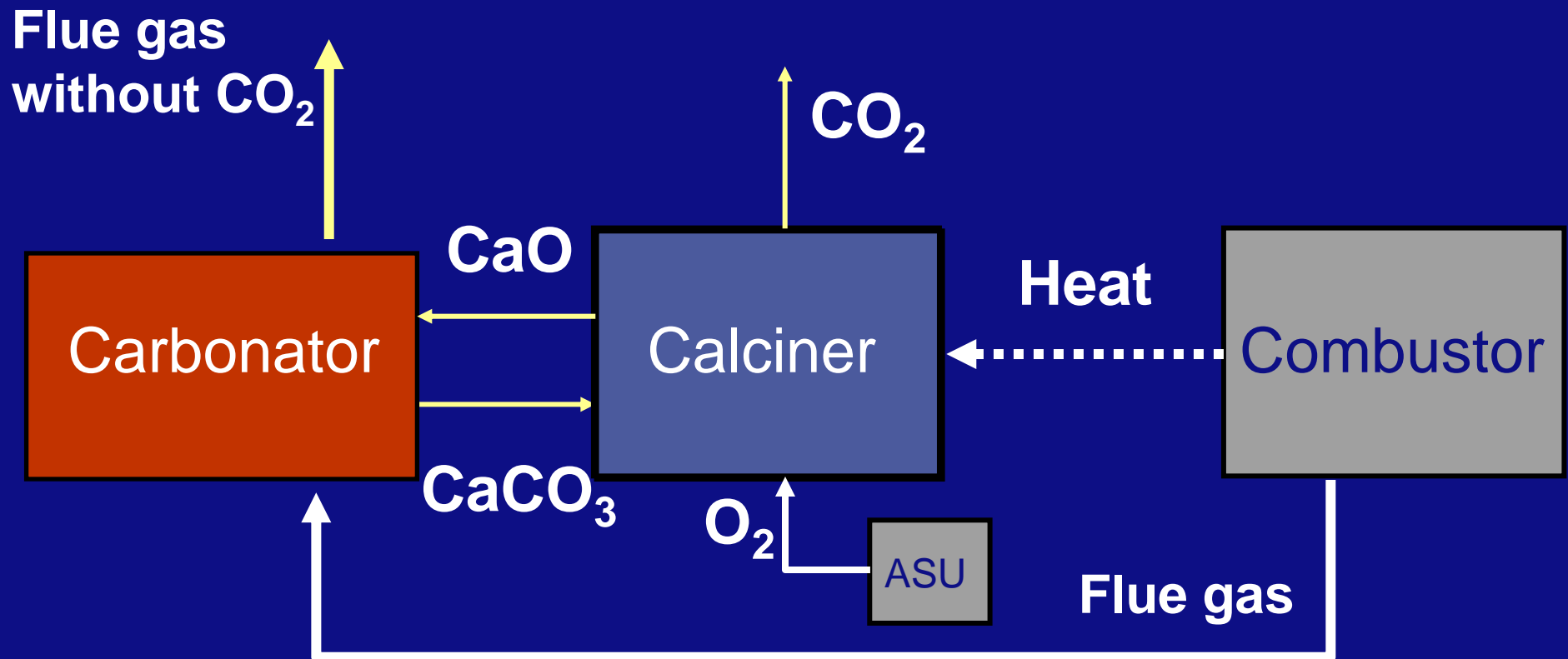


# Summary of economic assessment (80 – 95% CO<sub>2</sub>-removal; No CO<sub>2</sub> compression)

Solvent process	MEA	DECAB
Avoided costs for pulverised coal fired	32 – 36 Euro/ tonne CO <sub>2</sub>	15 – 16 Euro/ tonne CO <sub>2</sub>
Avoided costs for natural gas fired combined cycle	41 – 46 Euro/ tonne CO <sub>2</sub>	22 – 23 Euro/ tonne CO <sub>2</sub>



# The Lime Carbonation Calcination Cycle (Courtesy of INCAR – Dr. Carlos Abanades)



- Integration with cement manufacturing
- Cheap sorbent
- Retrofit possible

# Conclusions

- ❑ Post-combustion capture presents the decarbonisation approach with least impact on power generation processes
- ❑ Capture readiness is relatively simple to take into account for post-combustion capture
- ❑ Large potential for improvement post-combustion capture by “doing” and “searching”
- ❑ R&D programmes require an integrated approach to post-combustion capture
- ❑ Several advanced processes under development

