CASTOR: Progress in post-combustion CO_2 capture

Contribution to CO2NET EAST Workshop, Zagreb
27 February 2007

TNO | Knowledge for business

Paul H.M. Feron

Presentation Overview

- CO_2 capture introduction
- Post-combustion capture: State of the art
- CASTOR Integrated Project
- Post-combustion capture: R&D trends
- Final comments

CO_2 capture introduction

What are challenges for CO_2 capture?

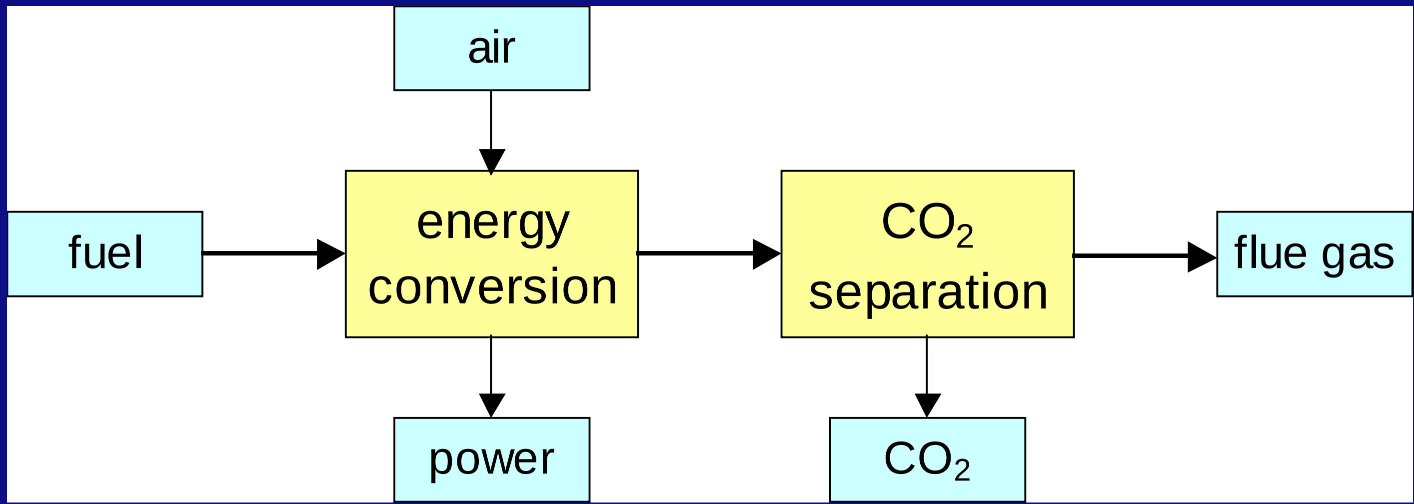
Capture of CO_2 can be done with technologies presently available but:

- Sizeable efficiency reduction
- Power generation costs will increase
- There is no experience with CO_2 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?
- How to make these processes reliable when integrated with power generation?

Post-combustion CO_2 capture
CO_2-removal from flue gases

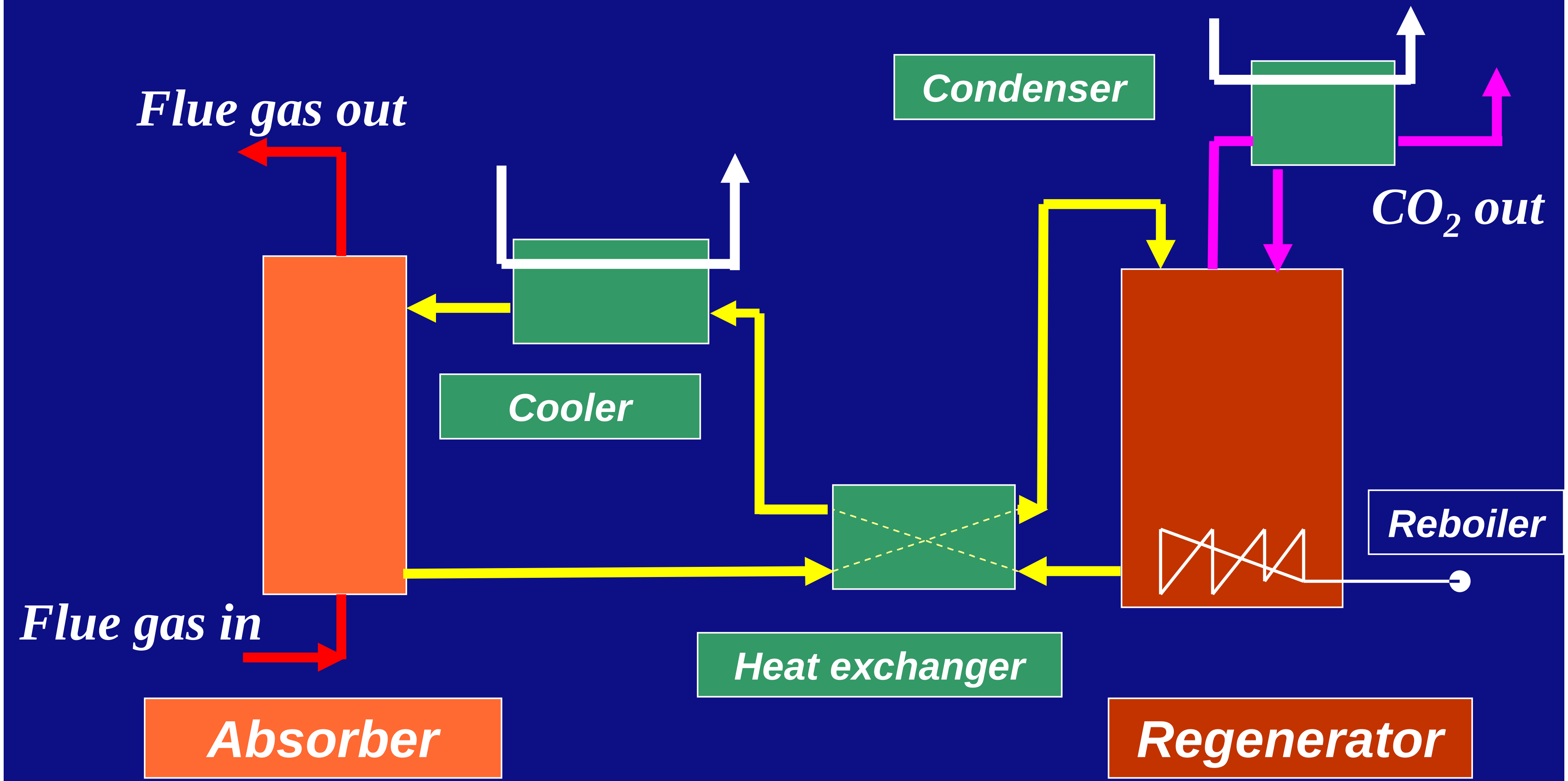


Why post-combustion capture?

- 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_2 capture process development
- Learning by searching will lead to better solvents and solvent processes

Post-combustion capture: State of the art

Solvent process flow sheet
Aqueous ethanolamine solutions



Ethanolamine reaction chemistry: General

q Primary, secondary amines (MEA, DEA)

Primary: $CO_2 + 2RNH_2$ à $RNH_3^+ + RNHCOO^-$
Secondary: $CO_2 + 2RNH$ à $RNH_2^+ + RNCOO^-$

- A carbamate with varying degrees of stability is formed
- High mass transfer
- Max. loading: 0.5 mol/mol amine

q Tertiary amines, sterically hindered amines (TEA, MDEA, AMP)

Tertiary: $CO_2 + RN + H_20$ à $RNH^+ + HCO_3^-$
Primary/sterically hindered:
$CO_2 + RNH_2 + H_20$ à $RNH_3^+ + HCO_3^-$

- Formation of bicarbonate in presence of water
- Low mass transfer
- Max. loading: 1.0 mol/mol amine

State of the art post-combustion CO_2-capture

- Fluor Daniel Econamine FG[SM]
  - 30% MEA solution incorporating additives to control corrosion
  - > 20 commercial plants in sizes between 0.2 and 15 tonnes CO_2/h
- ABB-Lummus
  - 15-20% MEA solution
  - 4 commercial plants in size between 6 and 32 tonnes CO_2/h
- Mitsubishi Heavy Industries
  - KS-1– sterically hindered amines
  - 2 commercial plants: 9 tonne CO_2/h
- More to come…..

Issues for post-combustion CO_2-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
  - Power plant concepts prepared for incorporation of capture plant

CASTOR

CO_2, from Capture to Storage

a European Integrated Project
(IFP – Project leader)

Consortium and finance

R&D	Oil & Gas	Power Companies	Manufacturers
IFP (FR)	STATOIL (NO)	VATTENFALL (SE)	ALSTOM POWER (FR)
TNO (NL)	GDF (FR)	ELSAM (DK)	MITSUI BABCOCK (UK)
SINTEF (NO)	REPSOL (SP)	ENERGI E2 (DK)	SIEMENS (DE)
NTNU (NO)	ENITecnologie (IT)	RWE (DE)	BASF (DE)
BGS (UK)	ROHOEL (AT)	PPC (GR)	GVS (IT)
BGR (DE)		E.ON-UK (UK)	
BRGM (FR)			
GEUS (DK)			
IMPERIAL (UK)			
OGS (IT)			
TWENTE U. (NL)			
STUTTGARTT U. (DE)			

Sponsor: ELECTRABEL (BE)

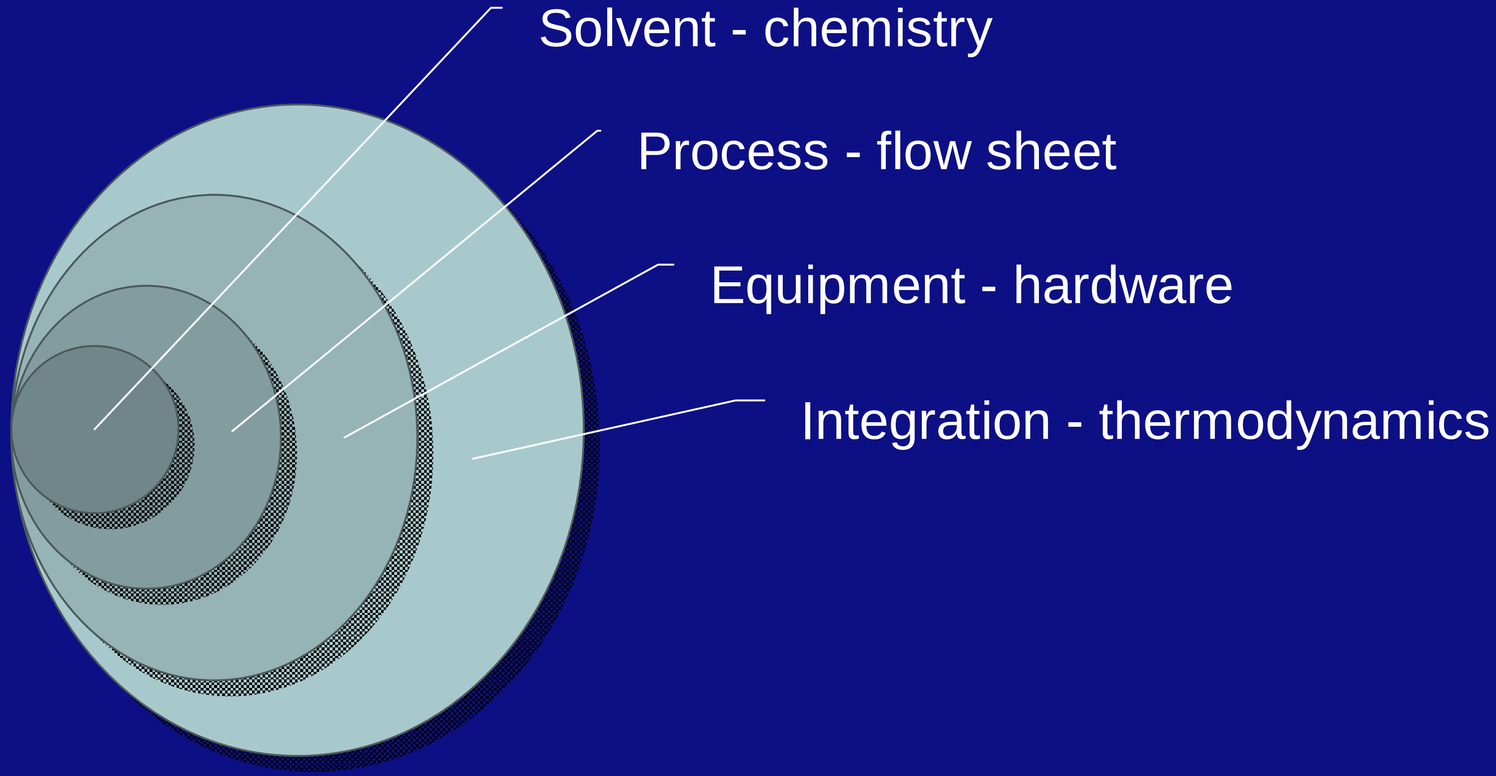
Budget: 15.8 M€
EU funding: 8.5 M€
Industrial funding: 2.2 M€
Duration: 4 years

Co-ordinator: IFP
Chair of the Executive Board: Statoil

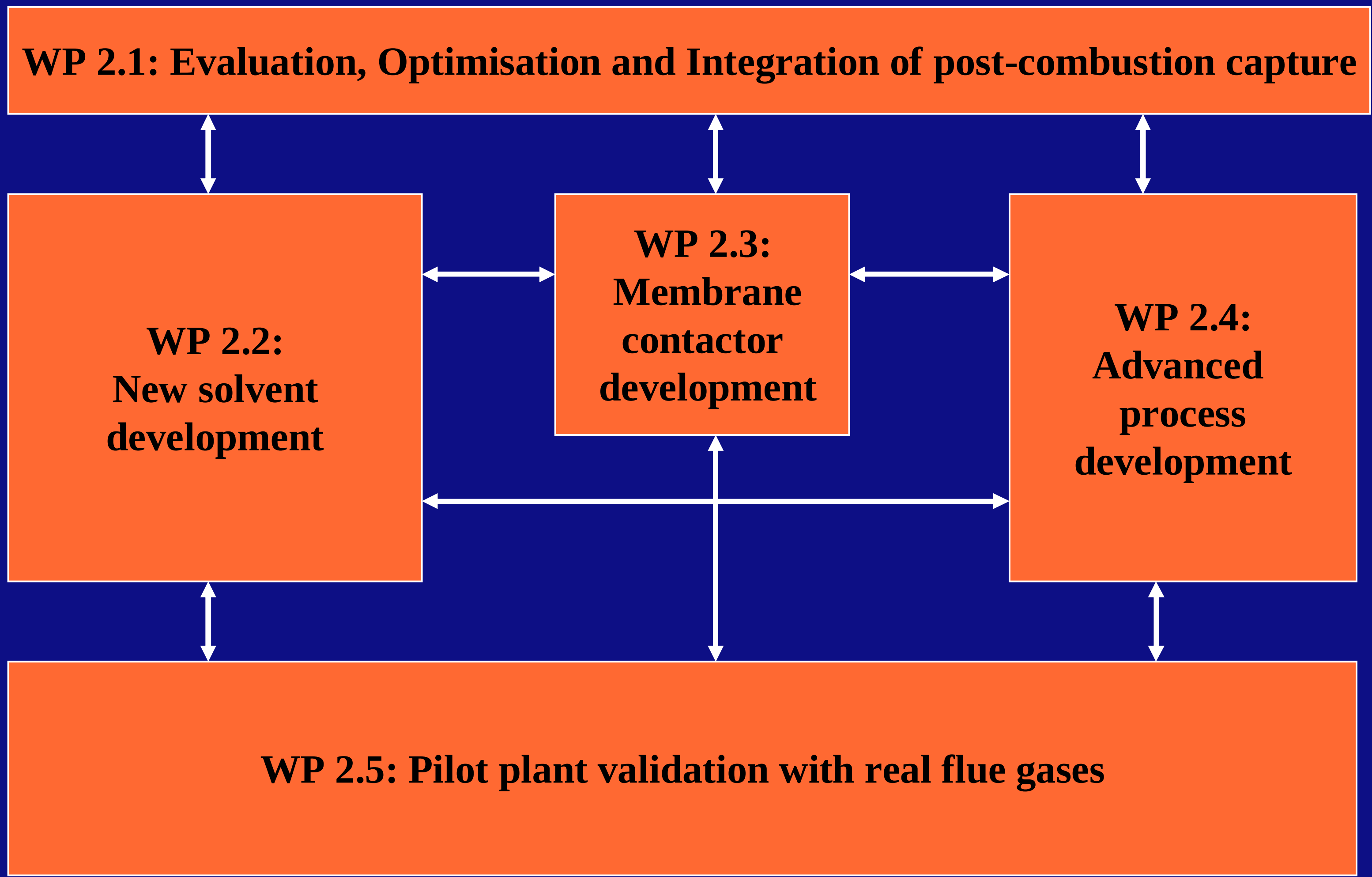
CASTOR Objectives / targets

- Reduce the cost of CO_2 post-combustion capture
- Contribute to the feasibility & acceptance of the geological storage concept
- Validate the concept on real site(s)
  - Pilot testing for capture (25 t CO_2 / day)
  - Follow-up of ongoing storage projects

Integrated approach in solvent process development for post-combustion capture



SP2 – Work package structure

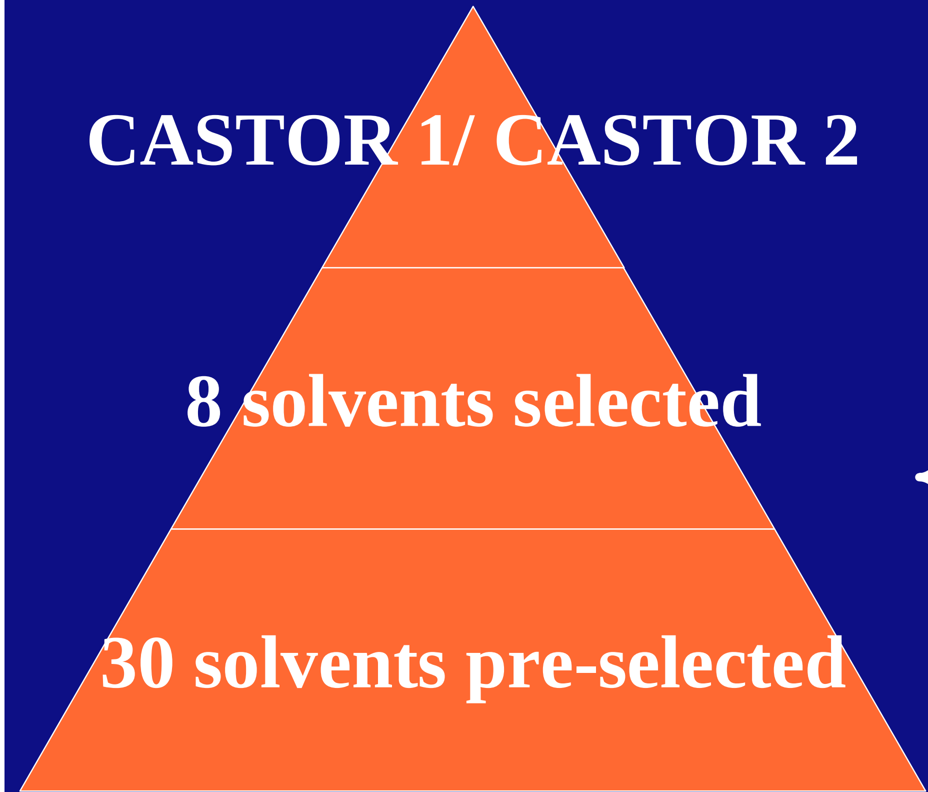


Solvent selection criteria

- **Cyclic capacity**
- **Regeneration energy requirement**
- **Rate of reaction/Mass transfer**

- Molecular transport properties
- Vapor pressure
- Corrosiveness
- Foaming properties
- Chemical stability
- Toxicity
- Water solubility
- Cost and availability

Solvent development procedure



Pilot plant experiments

↑

Lab-pilot experiments

↑

Process design studies

Degradation studies

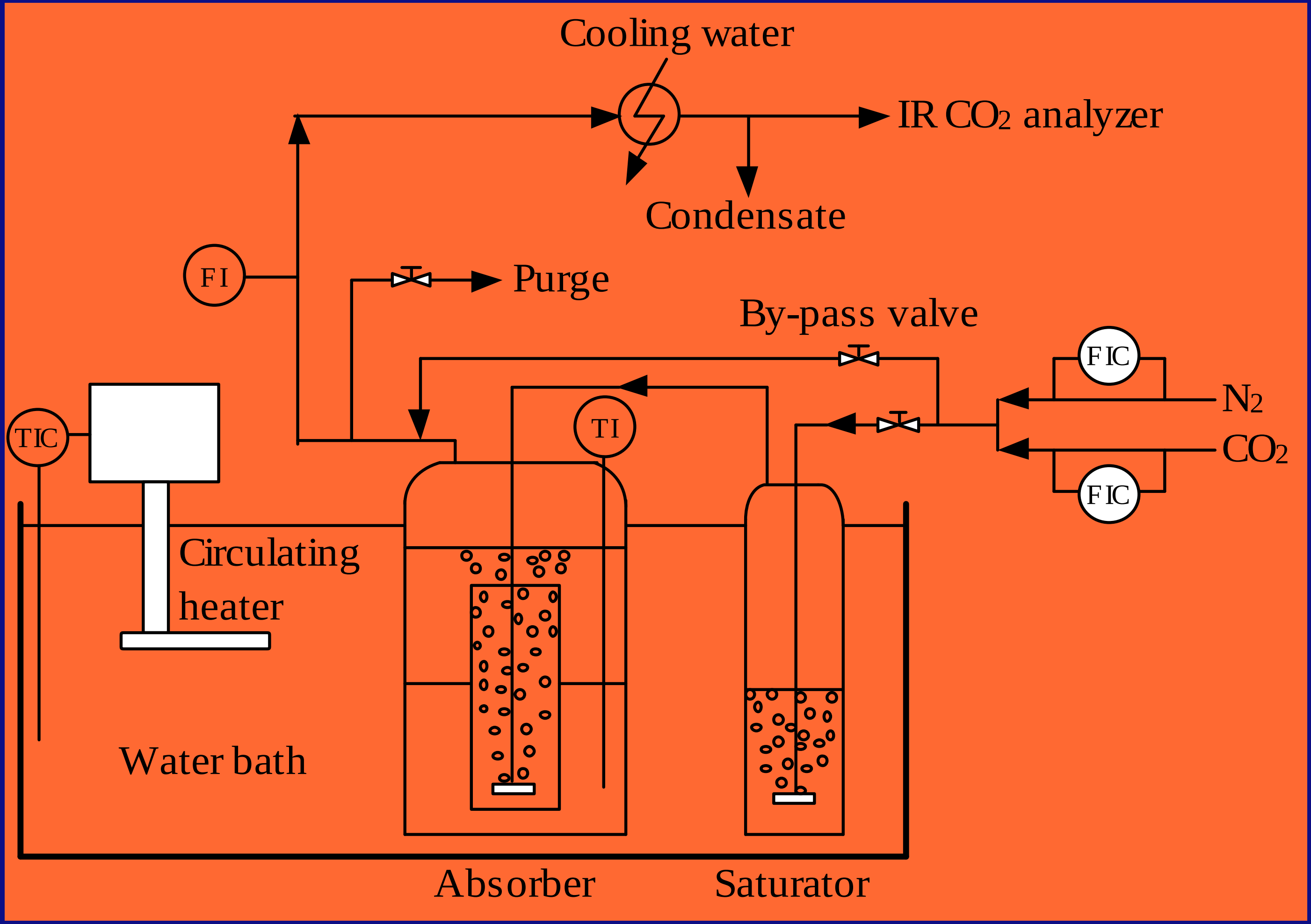
Corrosion studies

Solvent characterisation

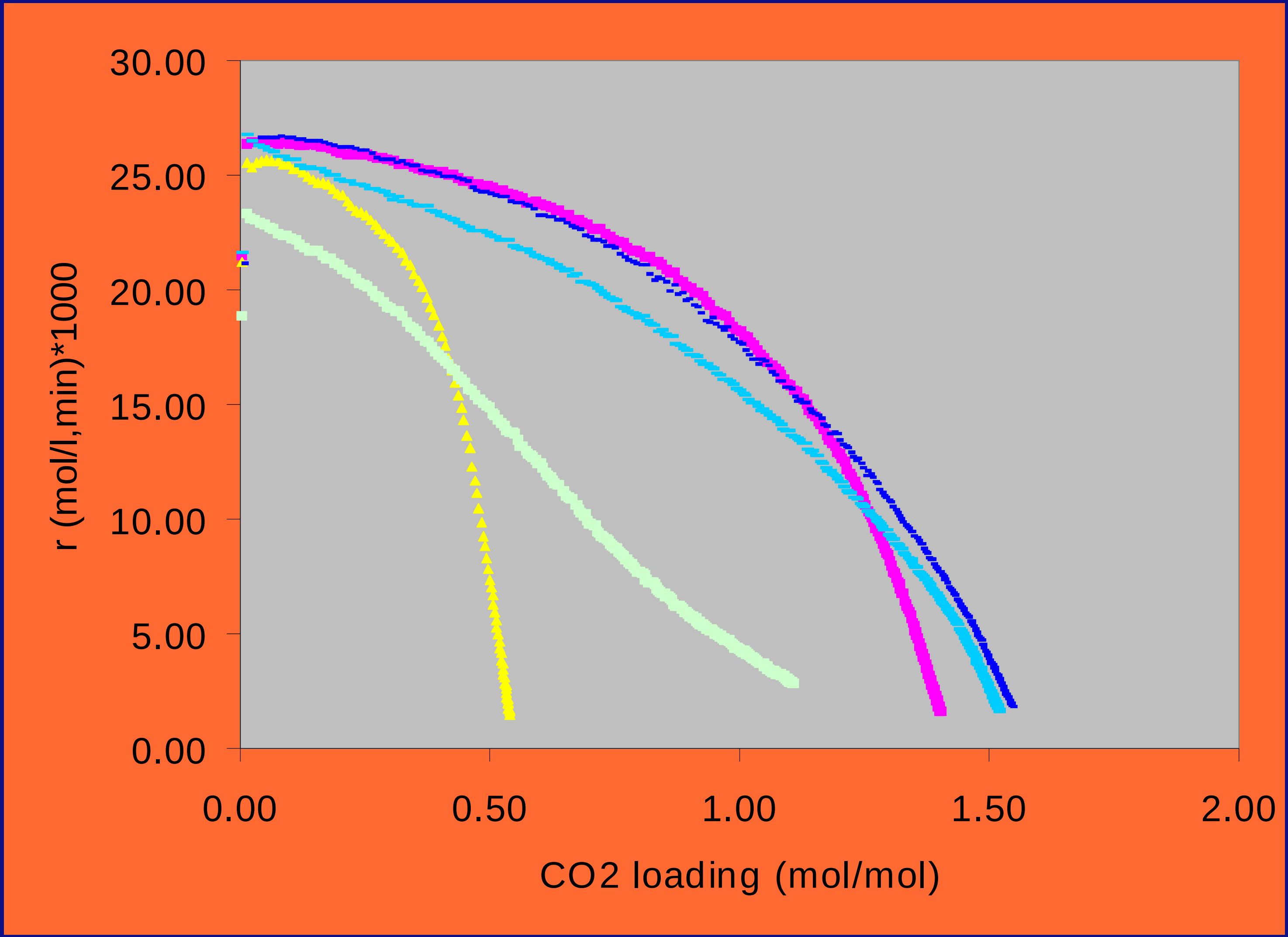
↑

Solvent screening studies

Screening apparatus for CO_2 absorption



Screening results - triamines



Experimental set-ups for solvent selection

Miniplant
Stuttgart Uni.

Degradation set up
Stuttgart Uni.

Equilibrium
Apparatus
SINTEF/NTNU

Corrosion test cell
IFP

Overview of consequences for European power plants CASTOR Results for base cases (30% MEA)

Item	Increase in investment	CoE Increase	Efficiency decrease	Cost per tonne CO_2 avoided
Gas fired combined cycle [393 MW_e]	48 %	51 %	18 %	54 €
Bituminous coal fired power plant [600 MW_e]	25 %	84 %	31 %	40 €
Lignite fired power plant [1000 MW_e]	17 %	88 %	34 %	40 €

Contributions to increase in CoE
CASTOR base case 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 %

Clean-up of flue gases – SO_2 capture

- Wet processes (liquor/slurry) achieve highest removal
- Technologies are available to achieve this
- Economics of these technologies have been mapped

FGD: Life cycle costs and marginal capture costs

	Bituminous 600 MW	Lignite 1000 MW	Lignite 380 MW
Limit	Cost Increase €/tonne CO_2	Cost Increase €/tonne	Cost Increase €/tonne CO_2
200 mg/Nm^3	0.000	0.000	0.000
50 mg/Nm^3	0.053	0.079	0.130
10 mg/Nm^3	0.077	0.151	0.231

EU Post-combustion capture test facility in Esbjerg Denmark (Dong Energy)

- Characteristics
  - Scale 1 tonne/h CO_2; 5000 m^3/h flue gas
  - Flue gases from coal firing
- Experimental programme
  - Solvent process validation for existing solvents
  - Solvent process validation for new solvents

Energy impacts for post-combustion CO_2 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_2-content in flue gas reduces specific power consumption
  - Solvent pumps, cooling water pumps:
    - Higher CO_2-loading of solvent reduces specific power consumption
  - CO_2 compressor:
    - Specific power consumption determined by pressure ratio

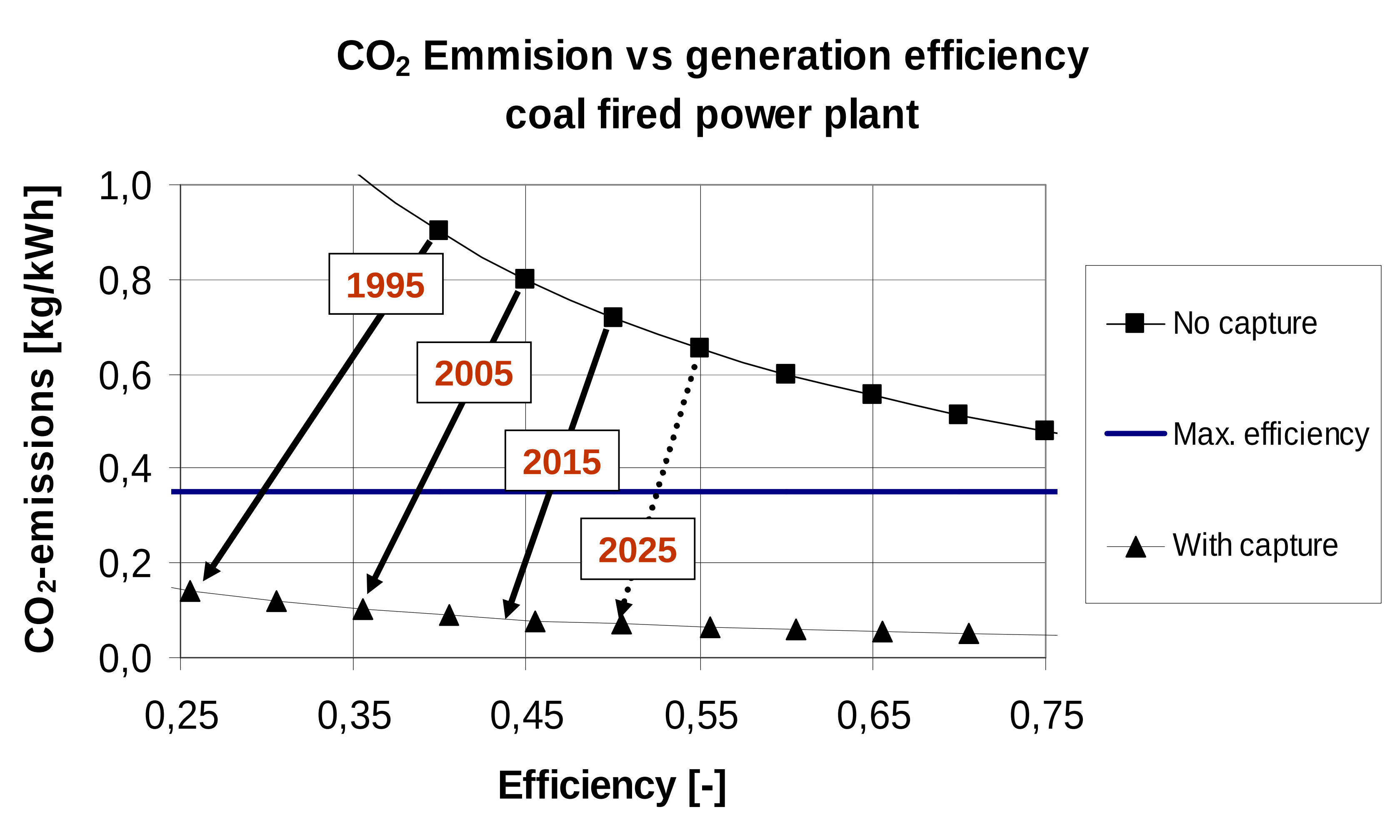
Post-combustion capture process performances: Past, present and future

Year	1995	2005	2015
Thermal energy	4.2 GJ/tonne CO_2	3.2 GJ/tonne CO_2	2.0 GJ/tonne CO_2
Power equivalent (Factor used)	0.292 kWh/kg CO_2 (0.25)	0.178 kWh/kg CO_2 (0.20)	0.083 kWh/kg CO_2 (0.15)
Power for capture	0.040 kWh/kg CO_2	0.020 kWh/kg CO_2	0.010 kWh/kg CO_2
CO_2 compressor	0.114 kWh/kg CO_2	0.108 kWh/kg CO_2	0.103 kWh/kg CO_2
Total	0.446 kWh/kg CO_2	0.306 kWh/kg CO_2	0.196 kWh/kg CO_2

Post-combustion capture in a coal fired power plant (Emission factor: 0.1 tonne CO_2/GJ)

Year	1995	2005	2015
Base plant efficiency	40 %	45 %	50 %
Base plant emission	900 kg CO_2/MWh	800 kg CO_2/MWh	720 kg CO_2/MWh
Power loss due to capture	0.446 kWh/kg CO_2	0.306 kWh/kg CO_2	0.196 kWh/kg CO_2
Plant efficiency with 90% capture	25.5 %	35.1 %	43.6 %
Emission with 90% capture	141 kg CO_2/MWh	103 kg CO_2/MWh	82 kg CO_2/MWh

Development of capture technology hand in hand with generation efficiency improvements



CAPRICE (Awarded in last EU FP6 call)

- CO_2 capture using Amine Processes: International Cooperation and Exchange
- Cooperation between CASTOR core partnership with consortium around International Test Centre on CO_2 capture (University of Regina, Canada)
- TNO, NTNU, Stuttgart University, IFP, Elsam, Energie E2, E.ON-UK
- Other CSLF countries involved: China, Russia, Brazil
- Budget: 1.144 M€ (0.383 EC contribution)
- Period: 2 years

Project activities:

1. Benchmarking and validation of amine processes
2. Membrane contactor validation studies
3. Development of tools for integration

Post-combustion capture: Research and development trends

Overview of 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 for absorption/desorption
- Robust solvents
  - Ammonia

Final Comments

- Post-combustion capture presents the decarbonisation approach with least impact on power generation processes
- Relatively simple to take incorporate capture plant in power plant for post-combustion capture
- Large potential for improvement in post-combustion capture by “doing” and “searching”
- R&D programmes require an integrated approach to post-combustion capture
- Several advanced processes under development show opportunities for efficiency improvement and cost reduction