CO_2 Capture Project

Capture Technology Overview

EU Roll-out

Bruxelles, June 2nd, 2004

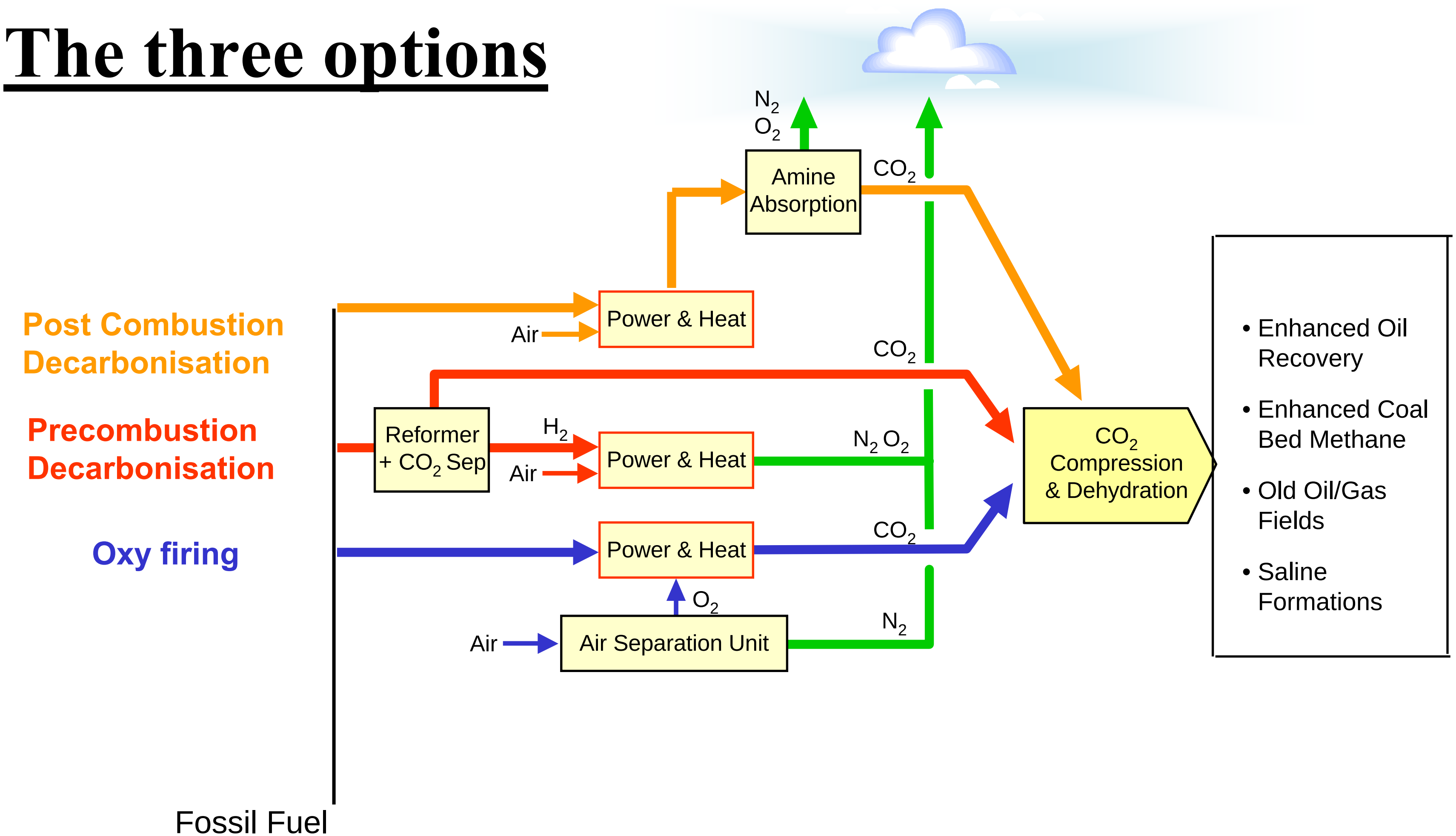
CO_2 Capture Project

US Department of Energy

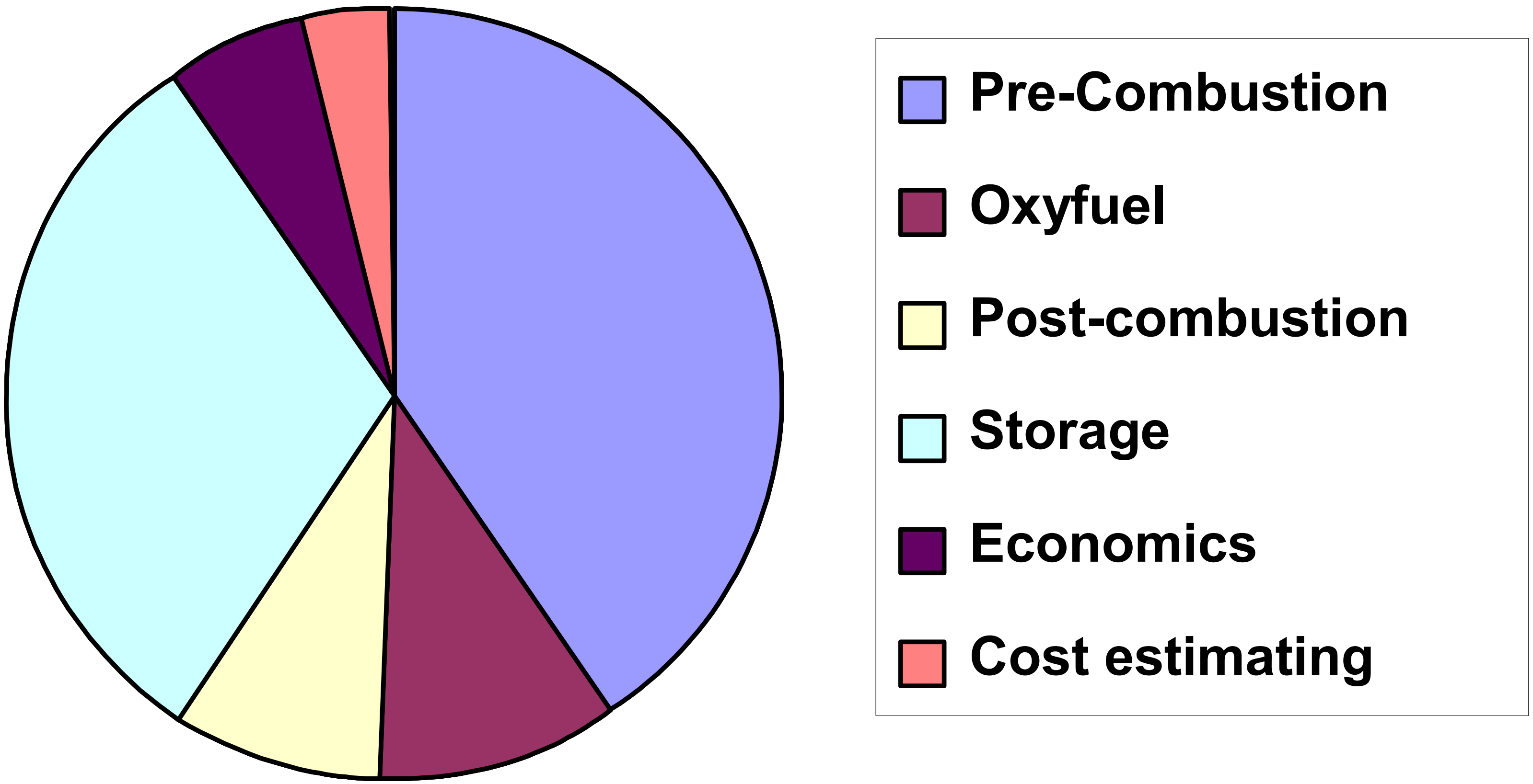
European Union

Klimatek NorCap

The three options



TOTAL FUNDING ~ 25 MMUS$



Scenario	Fuel	CO_2 Source	CO_2 Sink	Capture Target (MM tonne/yr)
Grangemouth Refinery in Scotland	Gas and Fuel Oil	Flue gas from heaters and boilers	Offshore EOR	2.0
Norway 385-MW power plant in Karsto, Norway	Gas	Flue gas from turbine outlet	Offshore EOR	1.1
Alaska Eleven 30-MW single cycle gas turbines.	Gas	Flue gas from distributed turbines	Onshore EOR	1.8
Canada Gasification plant	Pet Coke	Syngas from gasifier	Onshore EOR	6.8

Post-Combustion Overview

The Team:

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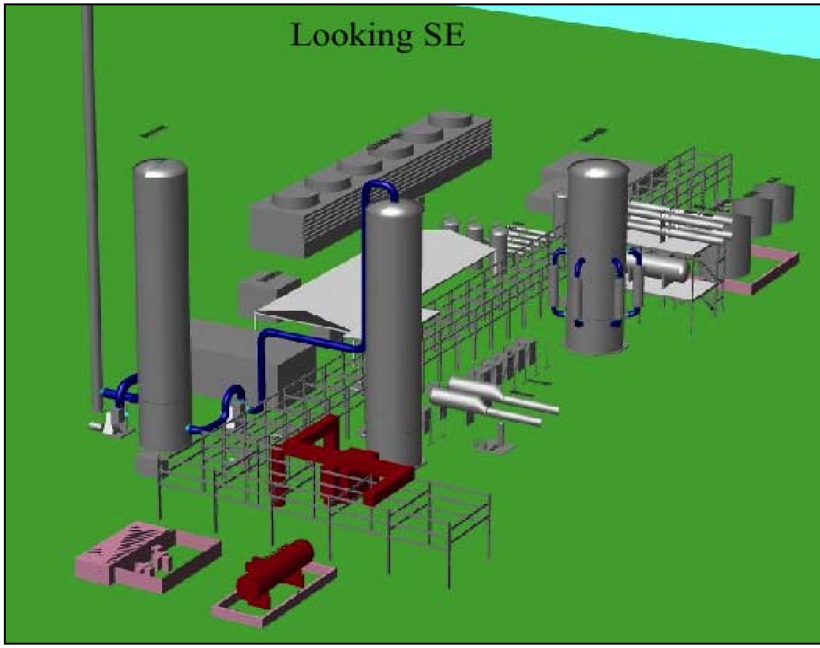
Post-Combustion: The Baselines

- **North European Refining and Petrochemical Complex.**
  - Amine Baseline Study to capture 2 million tpa CO_2 from heaters and boilers across the complex - with Fluor
- **Alaska Open Cycle Gas Turbines.**
  - Amine Baseline Study to capture 2 million tpa CO_2 from 11 open cycle gas turbine sets - with Fluor
- **Norwegian 400MW power plant**
  - Amine Baseline study to capture 1 million tpa CO_2 from power plant exhaust gases – with Fluor
- **Canadian Coal Gasification Plant**
  - Selexol Baseline study to capture 6.8 million tpa CO_2 from syngas – with Fluor

Key Outcomes – Absorption Based Technologies

- **Baseline studies…**
  - ➢Have established the technical feasibility and costs of post combustion CO_2 capture across scenarios.
  - ➢Highly energy intensive process…
  - ➢Technology largely proven (albeit not at this scale) and available today for retrofit.
  - ➢Requires coincidental removal of SO_x and NO_x (amine)
  - ➢It is high capital cost.



- **Key Issues are…**
  - –Low CO_2 concentration in flue gas
  - –Low pressure flue gas
  - –Large volumes of flue gas being handled

Post-Combustion Baseline Costs

Scenario	Incremental Capital Cost MMUS$	CO_2 Captured MMt/year	CO_2 Avoided MMt/year	CO_2 Avoided Cost (US$/ton)
Grangemouth Refinery in Scotland	362	2.19	1.55	78.1
Norway 385-MW power plant in Karsto, Norway	323	1.09	0.87	61.6
Alaska Eleven 30-MW single cycle gas turbines.	1012	1.90	1.96	88.2
Canada Gasification plant	519	6.80	5.22	14.5

Technology Areas Reviewed by the CCP

- **Absorption Processes**
  - Traditional Amine based –low cost & integrated designs.
  - Membrane based – using proprietary solvents.
- **Adsorption Processes**
  - PSA – using novel materials.
  - ESA – using carbon fiber composite mol sieve.
- **Other Processes**
  - Cryogenics
  - Compact Equipment Designs
  - Novel Concepts

Key Outcomes – Absorption Based Technologies

Amine Absorption Low Cost and Integrated Designs (Norway CCGT Power Plant).

- **Nexant Low Cost Design**
  Identify ideas for design simplification/cost reduction of post combustion CO_2 capture using amines (retrofit emphasis)

- **Nexant Integrated Design**
  Identify ideas for design and integration of post combustion CO_2 capture with new build CCGT.

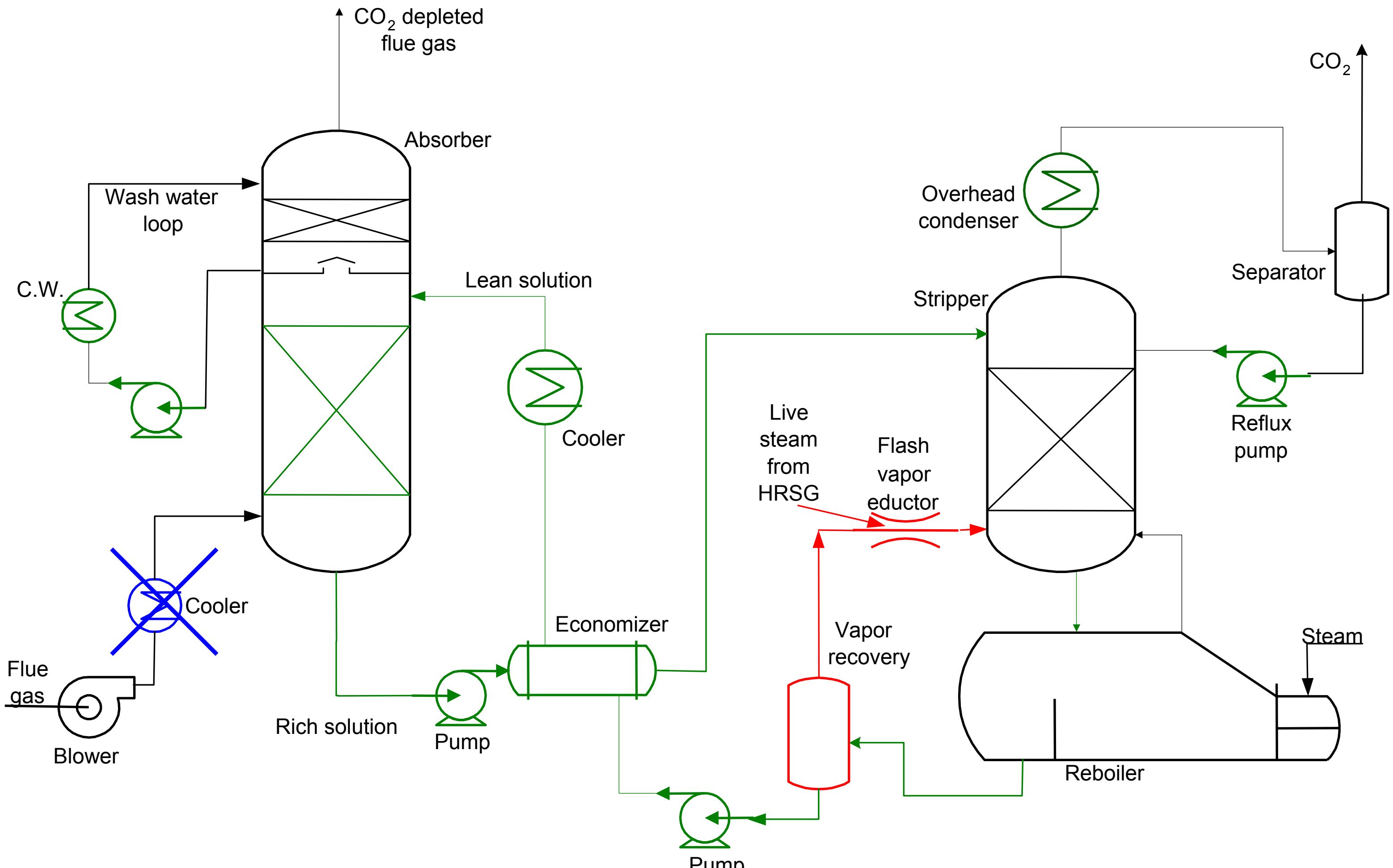
- **Combination MHI & Nexant (CCP 'BIT')**
  Application of design philosophy from Nexant (simplified and integrated studies) in conjunction with MHI's KS-1 solvent.

The Elements of Low-Cost Design

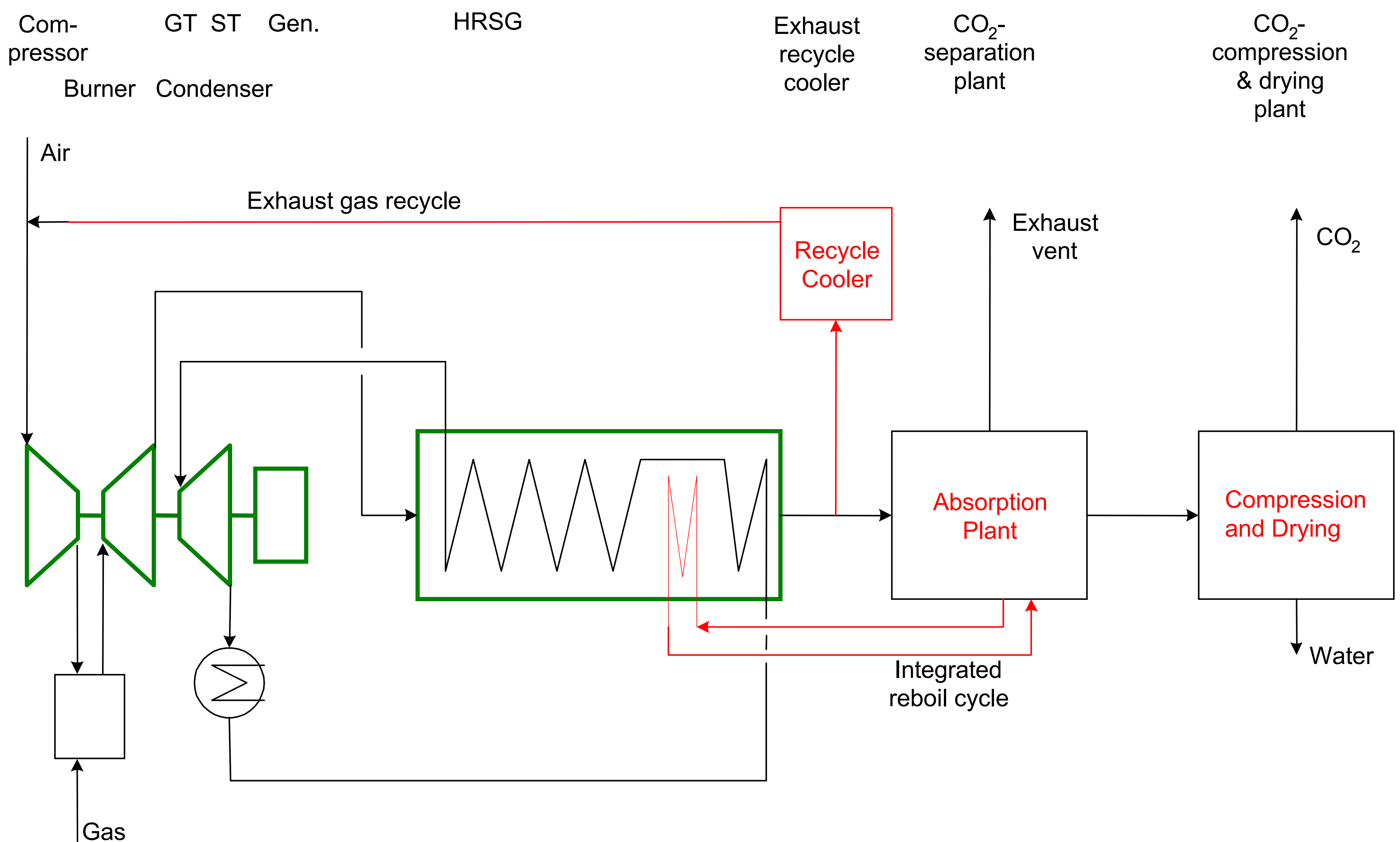
- No flue-gas cooler (absorber feed temperature of 80°C).
- Down-grading of gas blower and pumps.
- Plate & Frame exchangers rather than Shell & Tube.
- Structured packing rather than random.
- Lower overall reboiler by adding a vapor recovery system and live steam from HRSG.

- **Only for the BIT-case:** Solvent KS-1 by MHI rather than MEA (25% lower regeneration energy).

Low-Cost Capture Plant



BIT Integrated (Note: Solvent switched to KS-1)



Summary of Cost and Performance (by CCP)

	Net Power (MW)	Efficiency (%)	USGC Capex ($MM)	USGC Opex ($MM/yr)	USGC CO_2 Avoided Cost ($/tonne)
Uncontrolled	392	57.6	284	13	**N/A**
Base Capture	322	47.3	418	26	**60.0**
Low-Cost Capture	332	48.8	366	24	**44.7**
Low-Cost Integrated	335	50.6	345	24	**35.1**
BIT	**357**	**52.5**	**352**	**21**	**28.2**

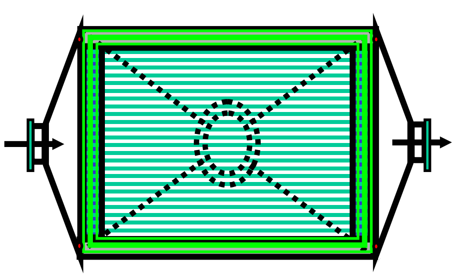
BIT Conclusions

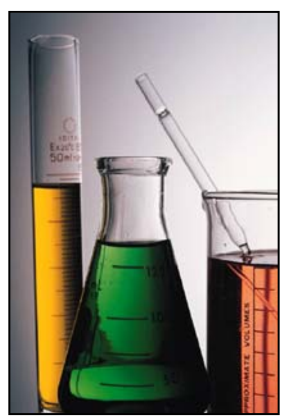
- BIT evolved from several, independent CCP projects
- Significant Cost-Reduction Potential (~50%)
- Further engineering work with turbine vendor needed
- Pilot testing for cost-saving ideas needed
- Improvements in solvents can improve BIT further
- Possible concern: acceptance of integration

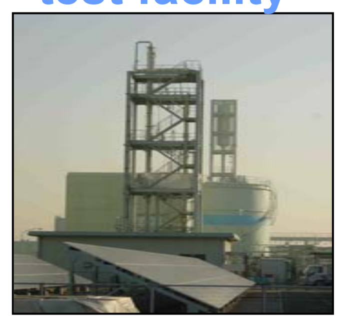
MHI / Kvaerner membrane contactor

- To develop an optimised process for CO_2 removal from flue gas
- By piloting the combination of Kvaerner's membrane contactor & MHI's KS-1 solvent technology

Kvaerner membrane + KS-1 solvent + MHI Nanko test facility = Pilot Demo in Japan





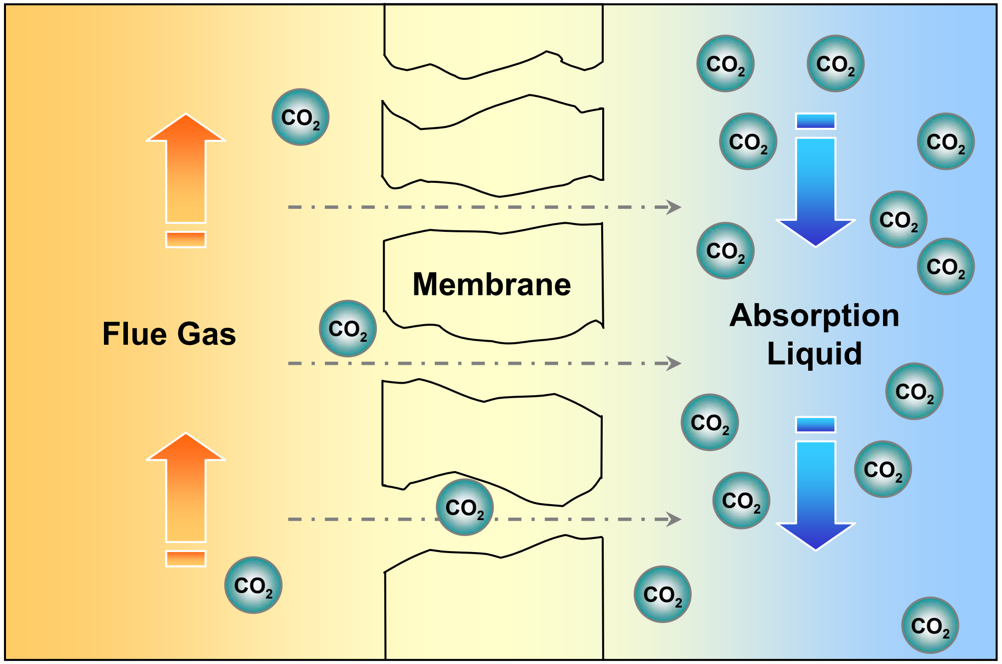


MHI / Kvaerner membrane contactor

- In the membrane gas/liquid contactor:

- Membrane physically separates flue gas containing 3 to 10% CO_2 from the KS-1 solvent

- Mass transfer of CO_2 occurs across the membrane due to absorption



Key Issue : Amine solvent migrates through the membrane requiring an additional flue gas clean up step.

Key Outcomes – MHI/Kvaerner Membrane

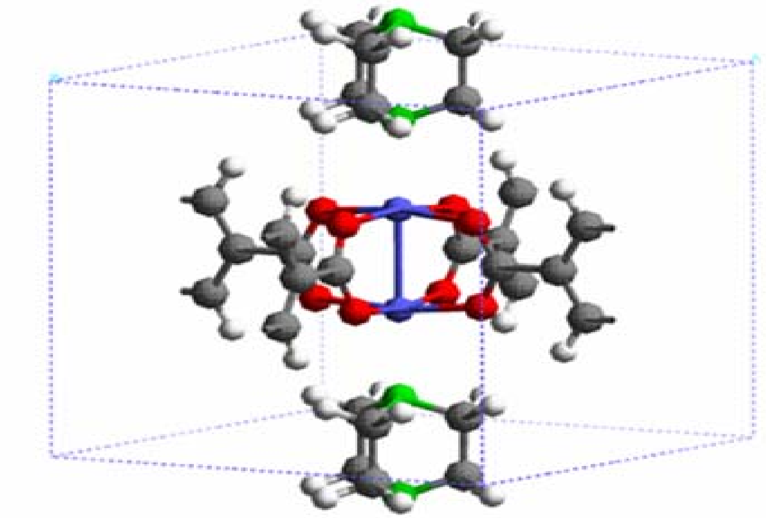
• Capital cost saving (versus conventional absorber/desorber equipment) are small and within the accuracy of the estimating technique.

• The principal advantage with this combination lies in the lower energy consumption of the KS-1 solvent (25% lower than MEA). Lower operating cost.

• The membrane system has a much smaller footprint and a much lower weight than conventional equipment. It will have an advantage where space and weight are at a premium….offshore.

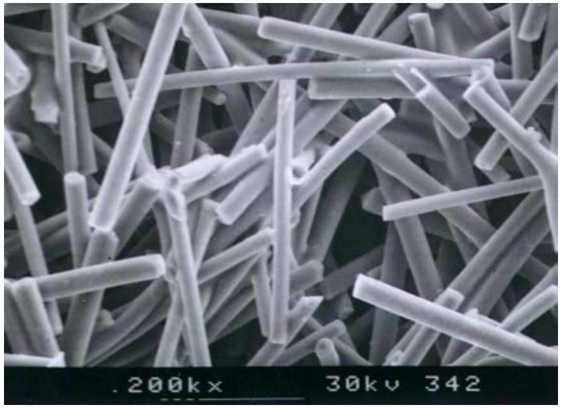
• Reduction (versus baseline) in Cost of CO_2 Capture is 19%. Majority of this comes from operating cost reduction.

Key Outcomes – Adsorption Based Technologies



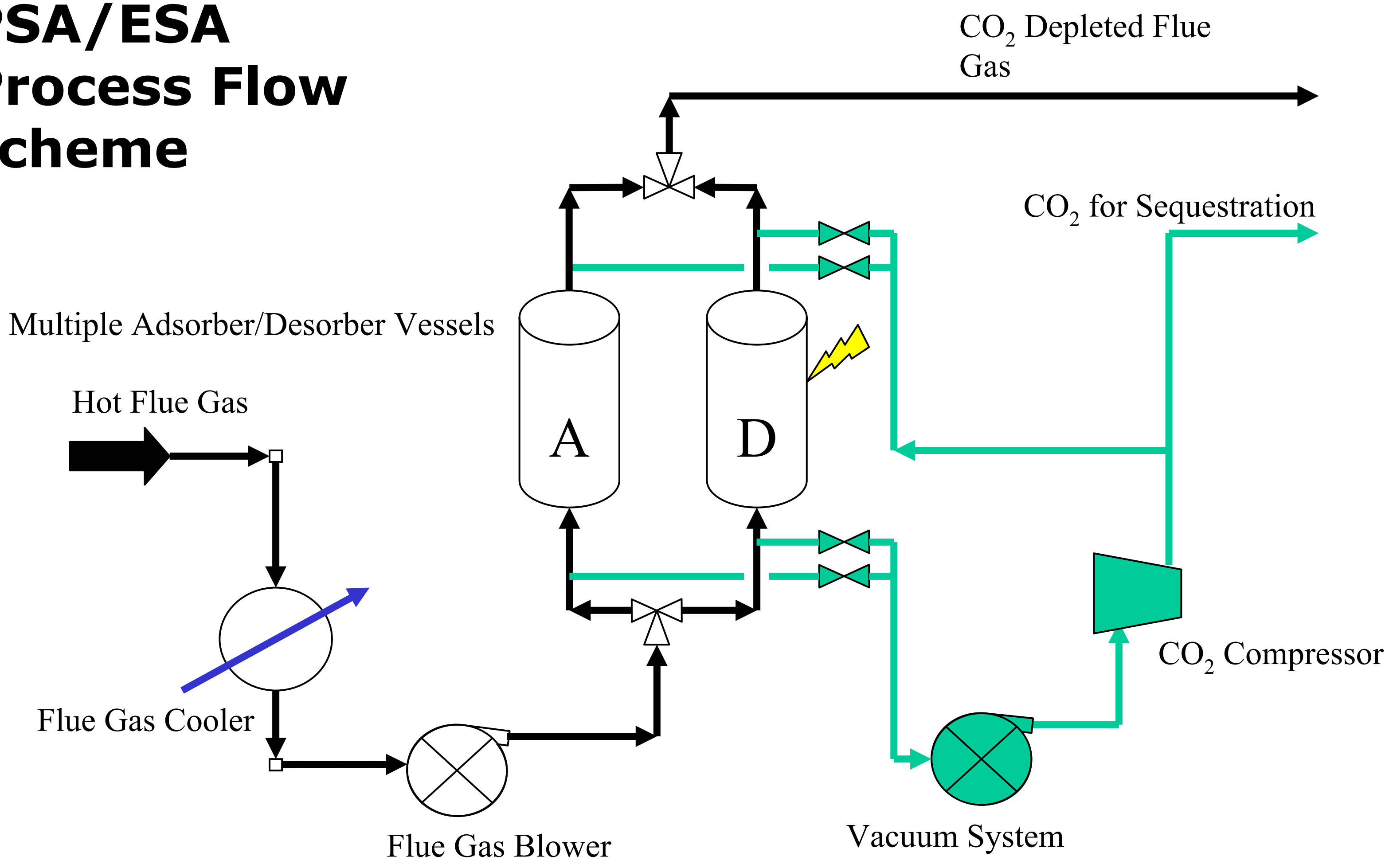
Two key Studies undertaken by the CCP

- SRI : Self Assembled Nanoporous materials.
  - Uses Copper Dicarboxylate materials.



- ORNL : Electric Swing Adsorption
  - Uses Carbon Fiber Composite Molecular Sieve material.

PSA/ESA Process Flow scheme



SRI : Self-Assembled Nanoporous Materials for CO_2 Capture….. Key Outcomes

- Simulation of a two-bed PSA system designed for a 400 MW gas fired power plant.
- Adsorption at exhaust gas pressure; desorption under vacuum.
- Recovery of 34.1% CO_2 at 67.9% purity.
- Sorbent weight:
  - SRI powder; 2,881 kg/bed;
  - SRI granulated; 5,549 kg/bed;
  - HISIV; 1,440 kg/bed.

Cost (per ton CO_2 captured):

SRI powder, $ 406.5

SRI granulated, $495

HISIV, $ 393.

- Power requirement for CO_2 capture: 1 GW.

ORNL : CFCMS material used with ESA for CO_2 Capture….. Key Outcomes

- CCP Internal engineering and cost review (Post Combustion at commercial scale) suggests 'no cost reduction potential' versus baseline amine technology.
- Low CO_2 loading on CFCMS requires multiple large Adsorber vessels and large CFCMS quantities.
- CFCMS pressure loss high – requires significant reduction for commercial feasibility.
- Requirement for substantial flue gas blower and regeneration vacuum systems – with attendant high cost.

Adsorbent systems all seem to suffer the same key problems;

- Low CO_2 loading due to low operating pressure
- Requirement to operate desorption under vacuum conditions

Other Processes and Novel Concepts

- Cryogenic Processes were rejected for study early on;
  - Drying
  - Freezing

- CO2 hydrate briefly considered but cooling needs and partial pressure requirements appeared to make this impractical.

- Compact Equipment (Rotating Absorber/Desorber) was considered but development cost and schedule did not match available funds or timing for the CCP.

- Novel Chemistry approaches have been considered more recently, with pH swing and melting point swing processes planned for future evaluation.

Oxyfuel Overview

The Team:

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Tom Brownscombe
Karl Gerdes
Francesco Saviano
Mark Simmonds

Oxyfiring: Combustion with "pure" oxygen

- **Oxyfiring not currently used in typical large combustion systems because of:**
  - **Expensive air separation system.**
  - **Necessity of flue gas recycle to moderate temperature.**
- **In the perspective of CO_2 capture, oxyfiring has the unique advantage to generate an effluent stream almost exclusively composed by CO_2 and H_2O resulting in cheap and easy capture.**

Oxyfuel: The Background

- **Cryogenic air separation is a mature technology with very little possible improvement.**
- **Large R&D ongoing Projects to develop novel "breakthrough" technologies for air separation with the target of commercialization by 2008-2010.**
- **Research in the field largely independent from "greenhouse gases" concerns.**

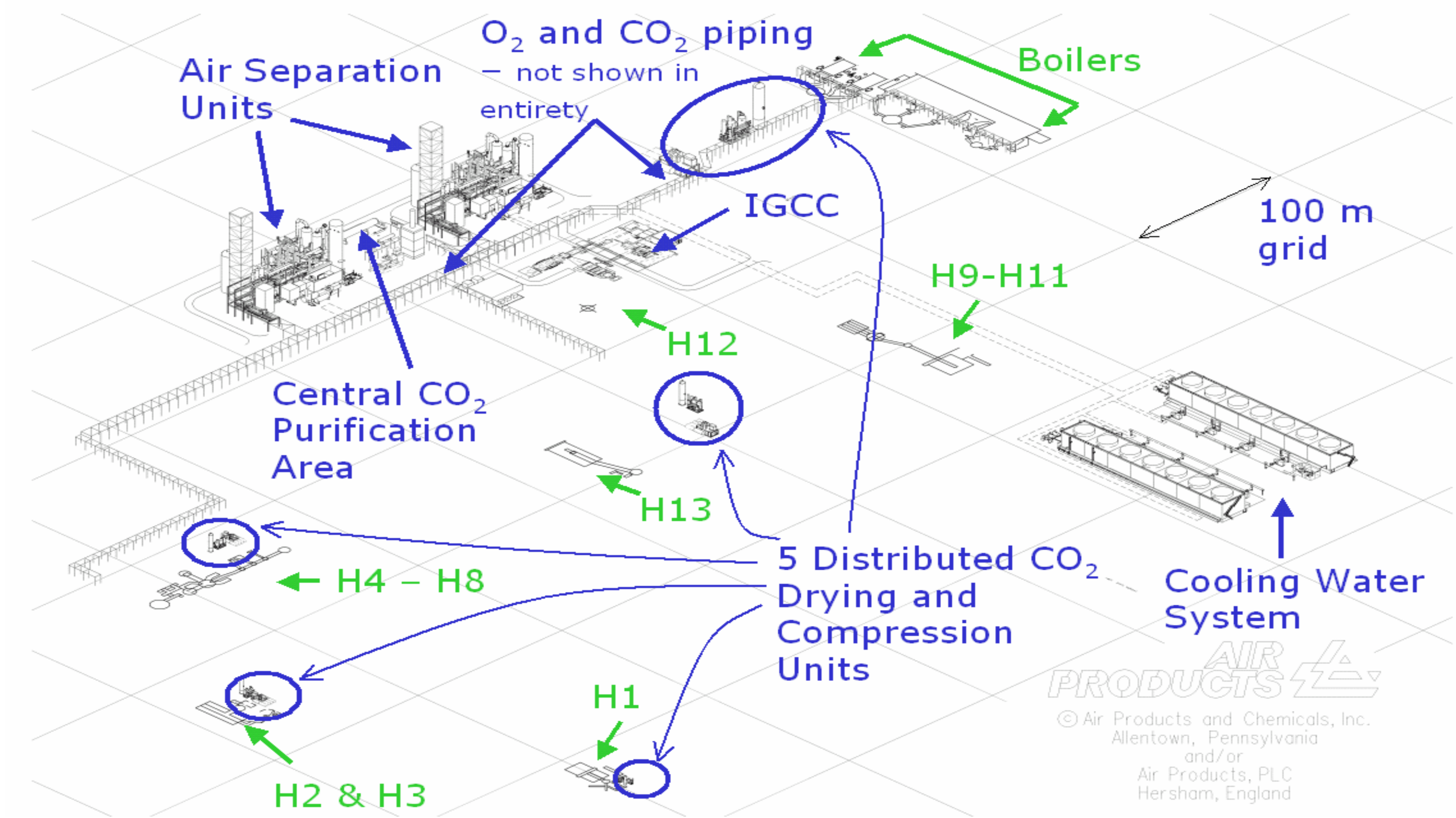
Oxyfuel Scope of Work

- Definition of an Oxyfuel Baseline by application of “state-of-the-art” technologies to the European Refinery Scenario.

- Investigation of the technical/economical potential of novel technologies or equipment, particularly:

  - Novel technological solutions for boiler revamping or new-building, maintaining cryogenic air separation (heaters have more uncertainties).
  - Advanced thermodynamic cycles for oxyfiring in power generation systems.
  - Novel air separation technologies for application to conventional boilers/heaters systems.
  - Novel technologies integrating steam or power generation systems and novel techniques for oxygen supply.

The Oxyfuel Baseline(1)



The Oxyfuel Baseline(2): Economics

	Post Comb. Baseline	Case 1: Cryogenic O_2 Base Case	Case 2: Cryogenic O_2 & offset steam	Case 3: Cryogenic O_2 & offset steam via H_2
Captured CO_2 (MMtons/year)	2.0	1.88	1.69	2.33
Avoided CO_2 (MMtons/year)	1.4	1.65	1.57	1.99
CO_2 Captured Cost (US$/ton)	55	38.0 (- 30.9%)	36.1 (- 34.4%)	33.8 (- 38.5%)
CO_2 Avoided Cost (US$/ton)	78	43.2 (- 44.6%)	38.9 (- 50.1%)	39.3 (- 49.6%)
Power Export (MWe)	Utility Neutral	10.7	3.4	(0.3)

- **Alignment by the CEM Team for Case 1 resulted in : CO2 capture cost: 44.4 US$/ton**
  CO2 avoided cost: 49.3 US$/ton

$\Rightarrow$ **Further 10$ reduction if NO_x credit is accounted for.**

The Oxyfuel Baseline(3): Main Conclusions

- Conversion of heaters and boilers to oxyfiring is technically feasible.
- Economic optimum for oxygen purity of 95%.
- Transport of concentrated O_2 raises additional (manageable) safety issues.
- One order of magnitude reduction in NOx emissions is also achieved.

- The Oxyfuel Baseline is applicable with consistent saving compared to any other available options, and low technical risk, so that implementation in Countries applying high level of Carbon Tax may be considered.

Novel boilers optimized for Oxyfiring of fuel gas or oil

- A few studies were commissioned to different Technology Providers to investigate potential savings achievable by optimization of boilers for oxyfiring:
  - High Pressure Boiler – Mitsui Babcock.

    Expected savings by reduced volume and power consumption.
  - Staged Combustion Boiler – Mitsui Babcock.

    25% reduction in fuel gas recycle at the expense of doubled footprint.
  - Zero recycle Boiler – Alstom/Praxair.

    No fuel gas recycle by using higher grade materials.

- No potential detected for consistent reduction in capture costs.

Advanced Oxyfuel Thermodynamic Cycles (1)

- **Evaluation by SINTEF of three different power generation concepts from the scientific literature based on stoichiometric oxygen combustion of Natural Gas and claiming high thermodynamic efficiency, to avoid the penalties related to air compression for separation and flue gas recycle:**

  - **Water Cycle, using water injection rather than Flue Gas Recycle to control combustion temperature.**
  - **Graz Cycle, similar to Water Cycle, with steam injection in the combustor.**
  - **Matiant Cycle, based on high temperature turbine and heat exchangers.**

Advanced Oxyfuel Thermodynamic Cycles (2)

- **Main conclusion is that the high efficiency claimed by all of the studied cycles are related to features requiring significant developments in gas turbine / steam cycle equipment, e.g.:**
  - **High temperature operation (turbine inlet at 1500°C or heat exchanged at 1000°C).**
  - **Low vacuum condensing (0.06 bara).**
- **All the cycles were about the same efficiency when compared on consistent bases.**
- **Turbine vendors not willing to engage in very expensive development without clear market perspectives.**

Novel Technologies for Air Separation

- **Different Consortia are developing ionic transport membranes for air separation with DOE and EU-funding for commercialization by 2008-2010**

Ion Transport Membranes (ITM)
Oxygen Permeable Ceramics

Typical ITM

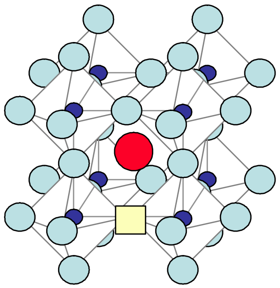
- Multi-component metallic oxide - mixed conductor

● = lanthanide ion

● = transition metal ion

○ = oxygen ion, O^{2-}

□ = oxygen ion vacancy



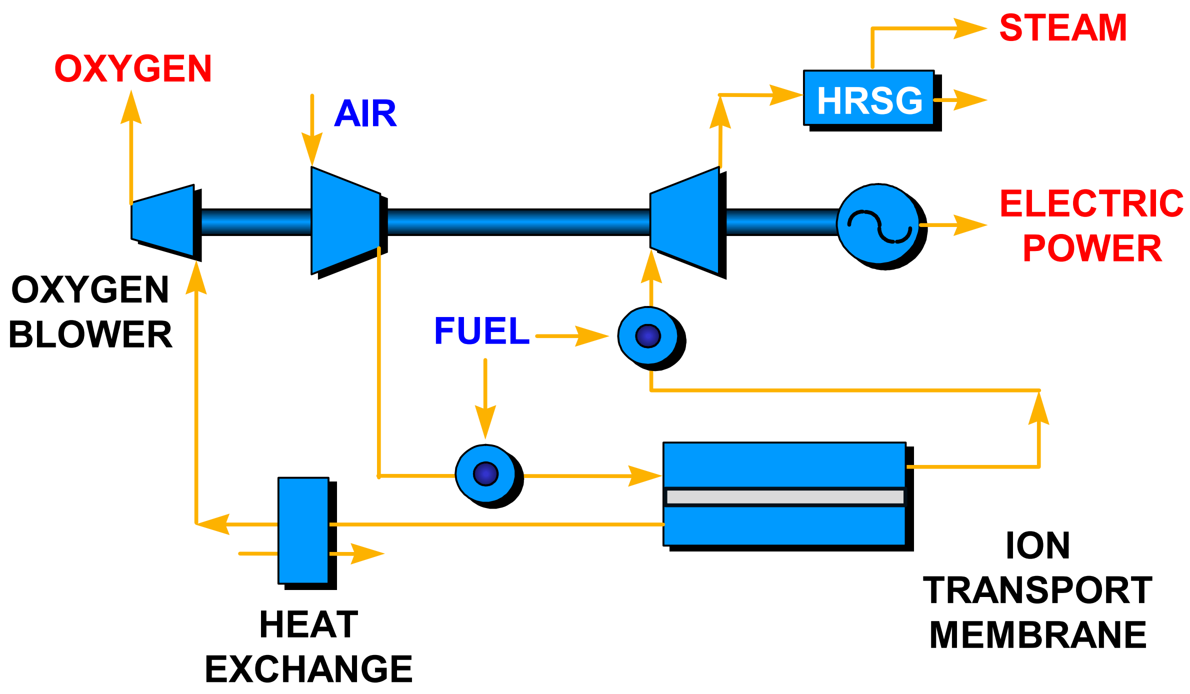
Vacancies built into the oxide by ion substitution

- Mobile at >700°C

Oxygen permeates at high flux and 100% selectivity

- Dependent on integrity of seals and membrane

Application of ITM (Air Products) in European Refinery



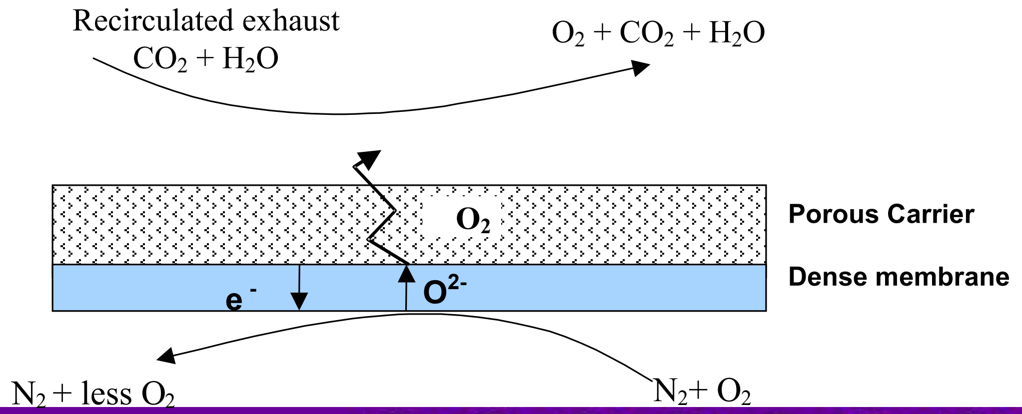
Economics of ITM in European refinery

Case	GT	O_2 reqd. Te/day	Total Power Reqd. (MW)	Export Power (MW)	CO_2 Captured (x 10^6 te/yr)	CO_2 Avoided (x 10^6 te/yr)
1	2 x V94.2	6626	54.7	446.2	1.89 / $33.5	1.71 / $37.0
2	2 x V94.2	3828	26.4	289.9	1.09 / $25.1	1.43 / $20.0
3	1 x V94.3	6051	71.3	121.4	2.62 / $28.5	2.06 / $38.1

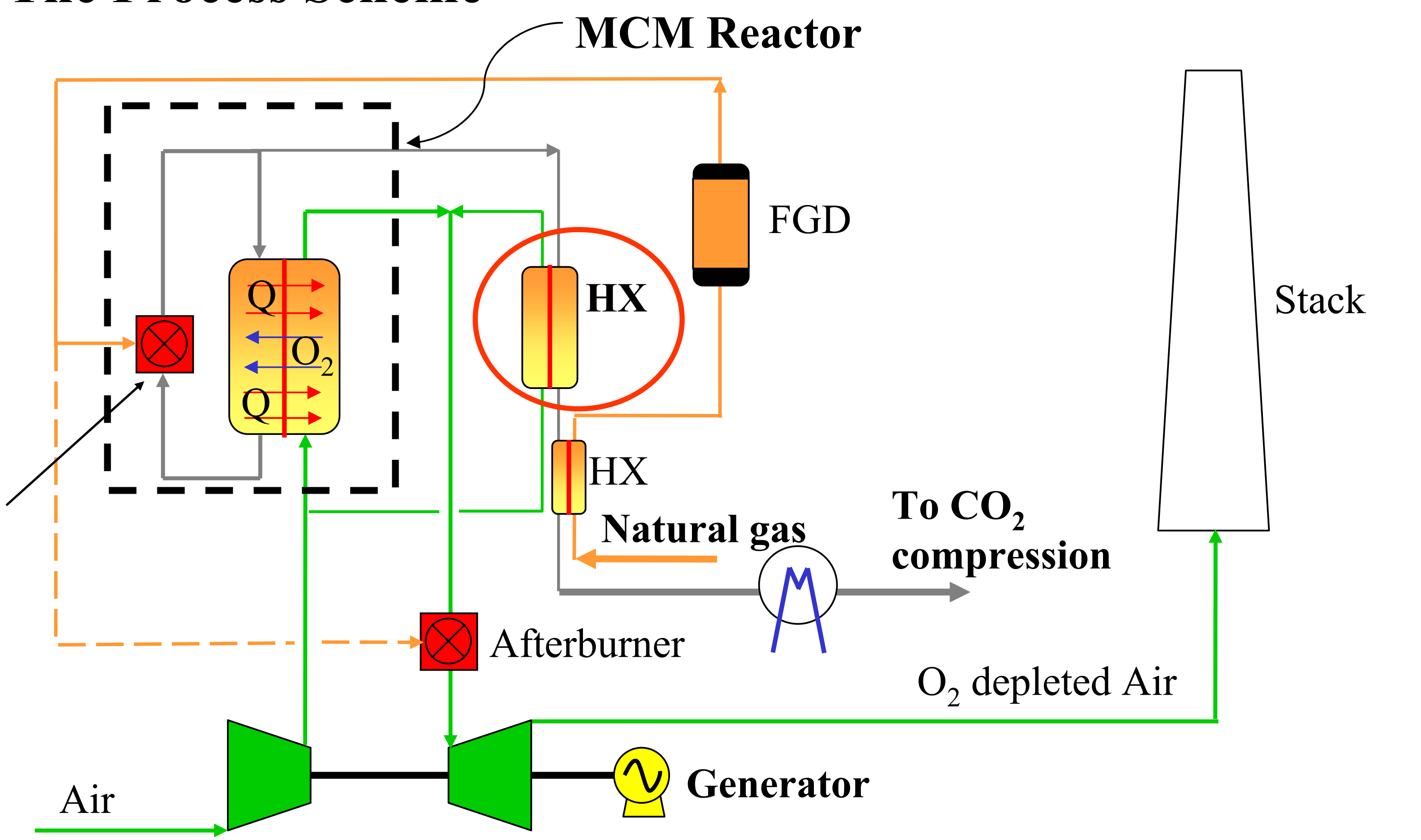
- **CCP alignment of Case 1 at about 30 US$/ton.**
- **Process scheme not fit for revamping unless there is market for power export.**
- **Promising option for new-built including CCGT systems for power generation.**

Novel integrated equipment - AZEP (Advanced Zero Emission Power)

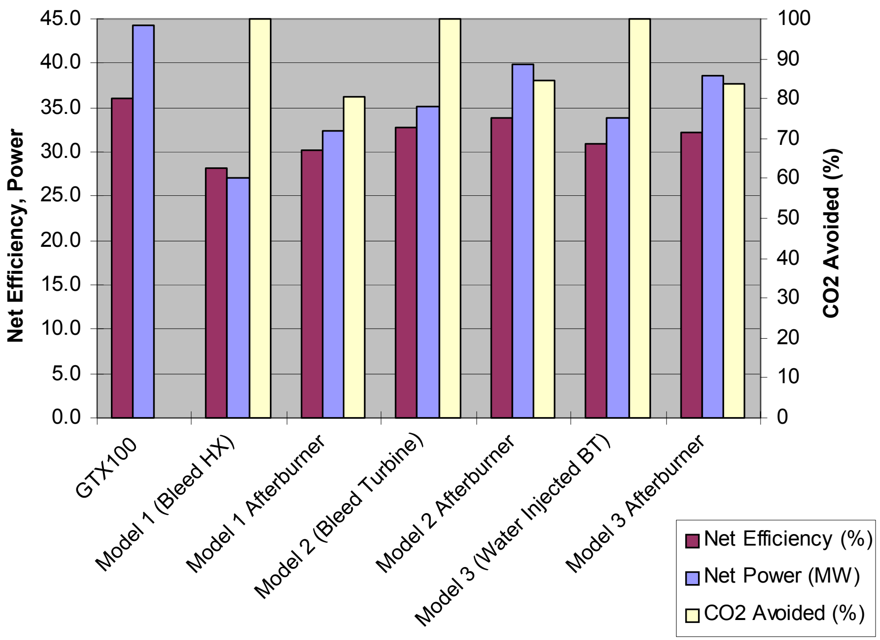
- **AZEP is developed by Alstom/Norsk Hydro in the frame of a 3-years EU-funded Project started in January 2002.**
- **Technology is applicable to the CCP power generation Case Studies.**
- **Alaskan scenario was selected for the CCP study, since it is composed by relatively simple and small turbine systems.**
- **While the original concept calls for complete CO2 capture, the CCP study also includes options with 80-90% capture that may minimize the CO2 avoided costs.**

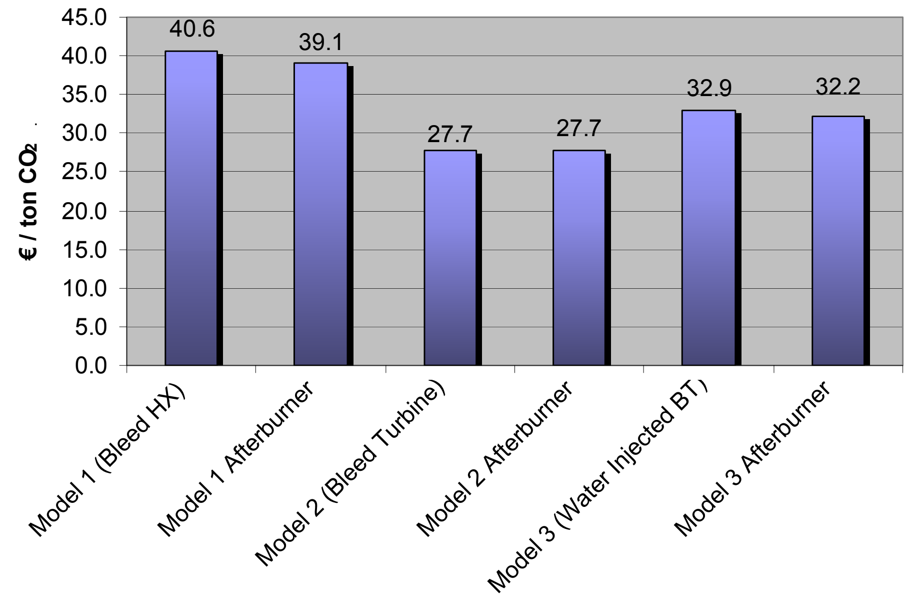


AZEP : The Process Scheme



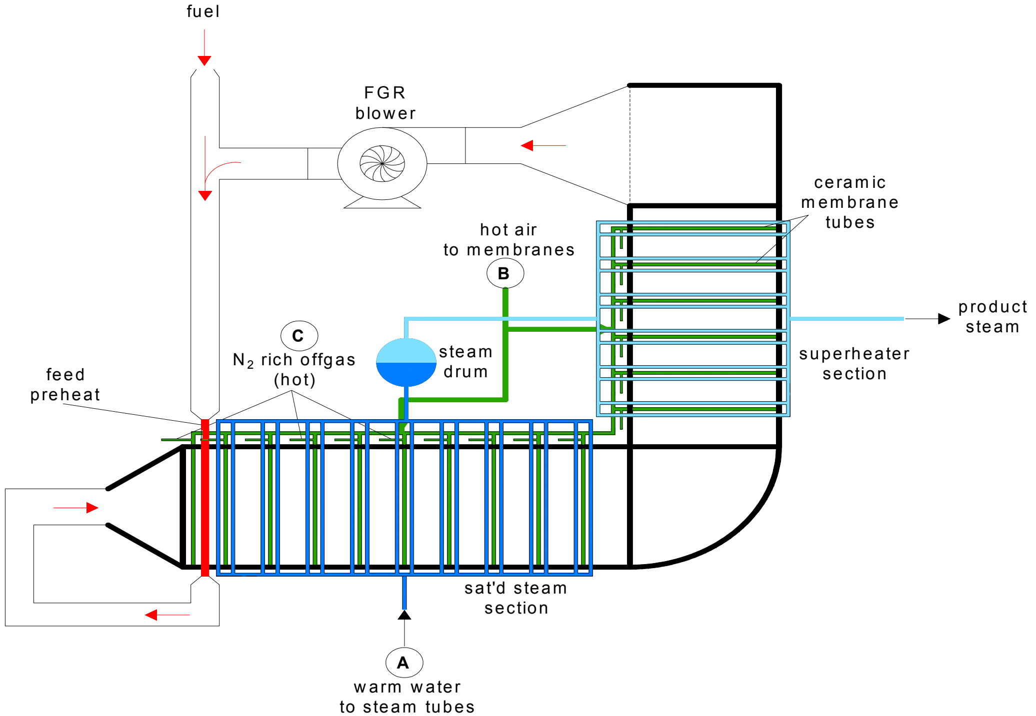
AZEP : Technical/Economical output





Praxair advanced boiler

➢ **Praxair is developing an advanced boiler, incorporating the OTM membranes in the frame of a DOE-funded Project whose target is achieving Proof-of-concept by 2006. The CCP and the DOE co-funded a study for application of the concept to replacement of a single boiler in the European Refinery Case Study.**

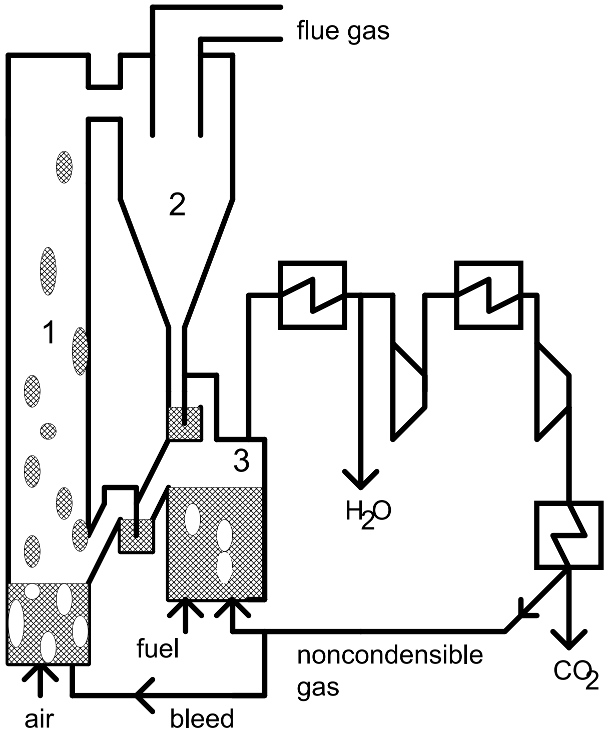


Praxair advanced boiler: economic results

- Boiler capital cost ~ 40% higher than conventional boilers.
- Total capital ~ 60% lower than conventional boilers with Post-combustion capture.
- Rough estimate based on Praxair data on CO2 capture cost at 15-20 $/ton.
- Concept still at an early stage of development: commercialization expected by 2009-2010.

Chemical Looping

- Chemical Looping is a new combustion technology based on oxygen transfer from combustion air to the fuel by means of a metal oxide acting as a solid carrier. Core of the technology is a two-reactors system with continuous circulation of solids:
- Fuel reactor: $4MeO + CH_4 \Rightarrow 4Me + 2H_2O + CO_2$
- Air reactor: $4Me + 2O_2 \Rightarrow 4MeO$



Chemical Looping (2)

- Technology under development in the frame of the GRACE Project co-funded by DOE and EU with a budget of 1.5 MM€ (1/2002 – 12/2003).
- Consortium formed By BP (Coordinator), Alstom Boilers, Chalmers University, Vienna University and CSIC (Consejo Superior de Investigaciones Scientificas).
- Achieved proof-of-feasibility of the Technology through successful operation of a pilot unit reproducing the features of future commercial units, at Chalmers. Alstom developed PFD, main equipment sizing and preliminary economic evaluation.
- R&D activity was limited to atmospheric pressure applications using Natural Gas as fuel. This technology may however be also applied to the typical pressure of combined cycles for power generation (20-30 bars), as studied in a DOE funded Project (outside CCP).
- Commercialization expected by 2010-2012 after operation of demo-unit (1MW) by 2008 and implementation of small commercial unit (40-50 MW).

Chemical Looping: main technical achievements

- **Proof-of-feasibility on pilot unit with continuous solid circulation and Ni- based carrier, including:**
  - **Reversible reduction/oxidation of the solid and oxygen transfer.**
  - **Almost complete methane combustion (99.5% at 800°C).**
  - **No gas leakage between reactors.**
  - **CO2 purity > 98% (impurities by equilibrium CO and H2).**
  - **Achieved solid circulation rate and reaction rate according to the hypotheses for economical evaluation.**
  - **No significant particle attrition or chemical decay observed.**

Chemical Looping: remaining uncertainties

- **Major concerns to be defined by further R&D are:**
  - **Catalyst ageing, both chemical and mechanical.**
  - **Scale-up of catalyst manufacturing procedure.**
- **Once material issues are solved, scale-up risk is moderate due to similarity with existing commercial technology (CFB).**
- **Possible application to high pressure**

Oxyfuel Key Outcomes

- **Oxy-firing offers the benefit to generate a flue gas stream containing only CO2 and H2O, making capture easy and inexpensive.**
  - **Oxy-firing can be practiced today using conventional air separation, along with flue gas recycle, in retrofit or new-built boilers and heaters at a cost of CO2 avoided about 30% less than the Post-Combustion Baseline.**
  - **In the longer term (2008-2010), CO2 avoided cost through Oxy-firing might be substantially reduced by advanced air separation technologies based on high temperature ceramic membranes, to the 20-30 $/ton range.**
  - **CCP identified Chemical Looping as a technology with the same potential for cost reduction than ceramic membranes in the 2010 time frame and co-funded a EU Project which achieved Proof-of-Feasibility through pilot plant operation.**
  - **An additional benefit of Oxy-firing is the drastic reduction (>90%) of NOx emissions.**
  - **Application with (gas) turbines requires further significant development to deal with the high temperature from this process.**

Pre-Combustion Overview

The Team:

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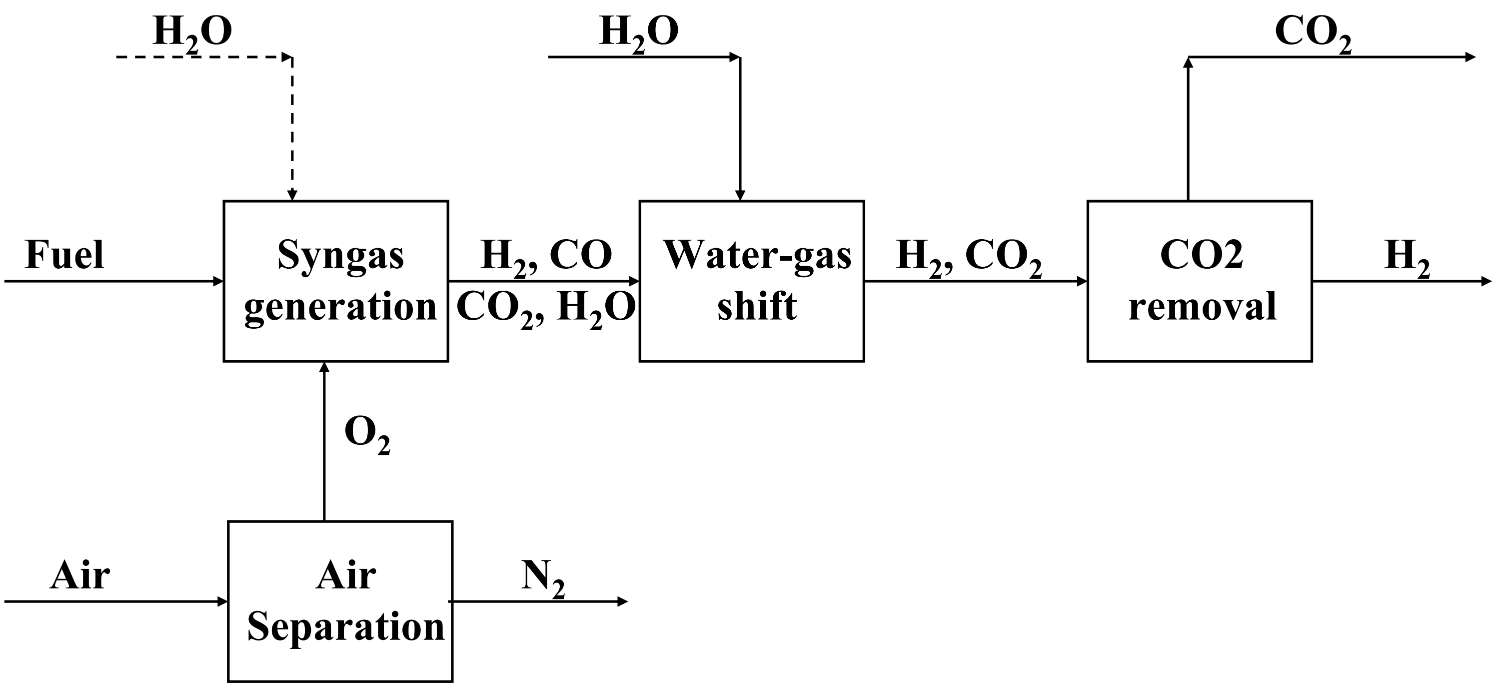
Jan Schelling

Pre-Combustion: the road through hydrogen



PCDC advantages…

- CO_2 removal via solvent absorption is proven
  - Elevated pressures and high CO_2 concentrations aid removal
- Possible production of CO_2 at moderate pressures (lower compression costs)
- Produces hydrogen
- Low SOx, NOx
- Flexible fuel sources (gas, oil, coke, coal, etc.)

…. and disadvantages

- Must convert fuel to syngas first.
- Requires major modifications to existing plants.
- Gas turbines, heaters, boilers, must be modified for hydrogen firing.

Precombustion Work Scope

- Verify potential benefits and define performance targets.
- Evaluate improvement of baseline through standardization and large capacity plants.
- Investigation of the technical/economical potential of novel technologies:
  - CO_2 removal tailored to PCDC (CO2LDSEP by Fluor).
  - Integration of WGS and CO_2 removal (MWGS, SEWGS).
  - Integration of syngas preparation and CO_2 removal (HMR).
  - Complete integration in a single unit (IFE).
- Evaluate enabling technologies (e.g. gas turbine firing with hydrogen).

- **Four large R&D Projects directly co-funded (with EU, DOE and Klimatek).**

Review and Evaluation Studies

- **Advanced syngas study – Foster Wheeler**
  - 400 MWe natural gas combined cycle power plant
  - Seven PCDC process schemes evaluated
  - No significant advantages over base PCDC plant
- **Hydrogen membrane study – Haldor Topsoe**
  - Membrane reforming, membrane water gas shift
  - Established targets for membrane performance
  - Verified potential cost savings
  - Showed disadvantage of upstream sulfur removal for coal gasification.

Possible improvements through standardization or large capacity

- **Very Large Scale ATR (by Jacobs)**
  - Single train production of H_2/N_2 mixture to support 1200 MWth of power.
  - 90% CO_2 Capture by MDEA washing.
  - < 20% improvement over baseline in CO_2 capture cost.
- **Standardized PCDC (by Jacobs)**
  - Standardization for integration in CCGT systems.
  - Modular design/construction, multiple identical units….
  - 15-20% cost reduction by 10th Unit.

CO2LDSEP: Potential best fit for coal gasification.....

- Simultaneously produces H2 and CO_2.
- Compressed feed gas enters an autorefrigeration plant where the CO_2 is liquefied in an expander
- Sulphur tolerant, H_2 delivered at pressure, high carbon recovery, high purity of CO_2
- Fluor has patented the process for use, among other things, in the recovery of CO_2 from hydrogen plant offgas, as well as from IGCC syngas
- Uses proven equipment and processes in a novel application (i.e. low technical risk)

.....but no clear advantages over standard washing (Selexol)

• Petcoke gasification unit in Canada co-produces hydrogen, steam and power (total of about 600MWe equivalent).

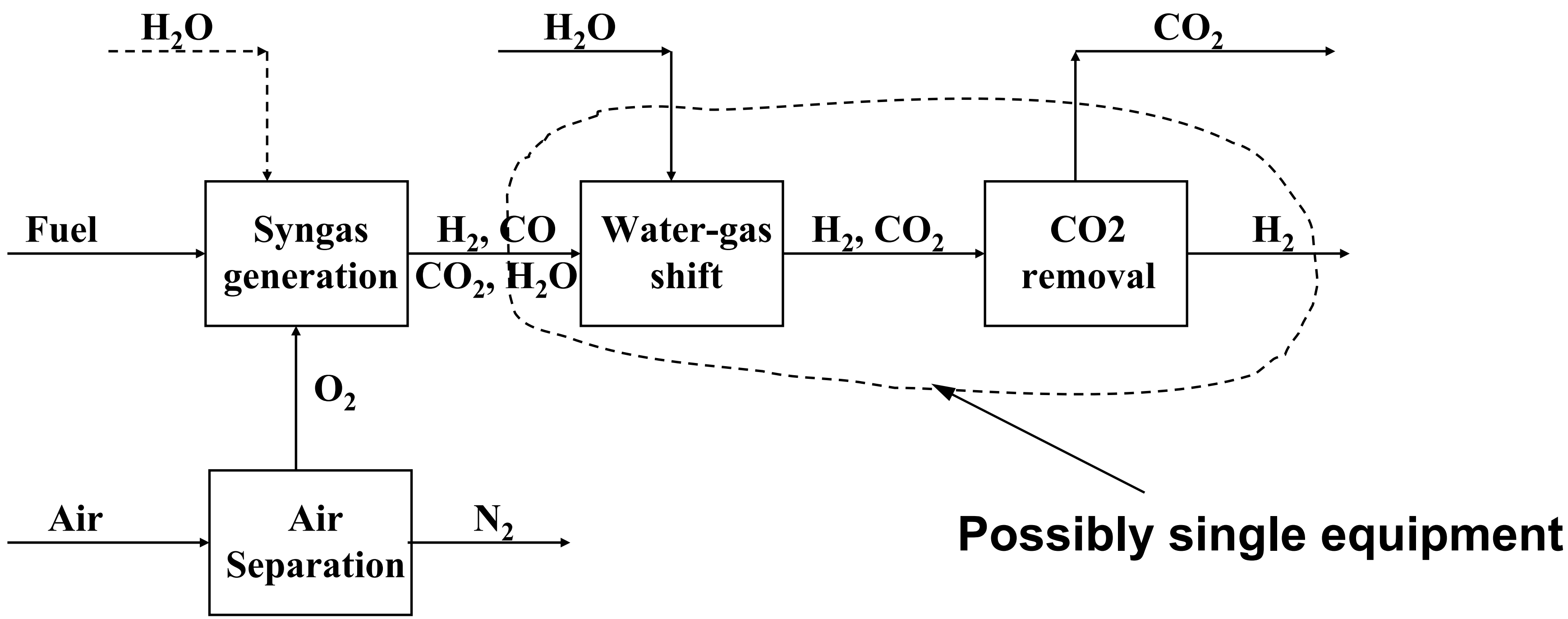
•As compared to the controlled baseline the CO2LDSep process requires less energy and generates an additional 35 MW of electrical power.

• Capex higher than baseline.

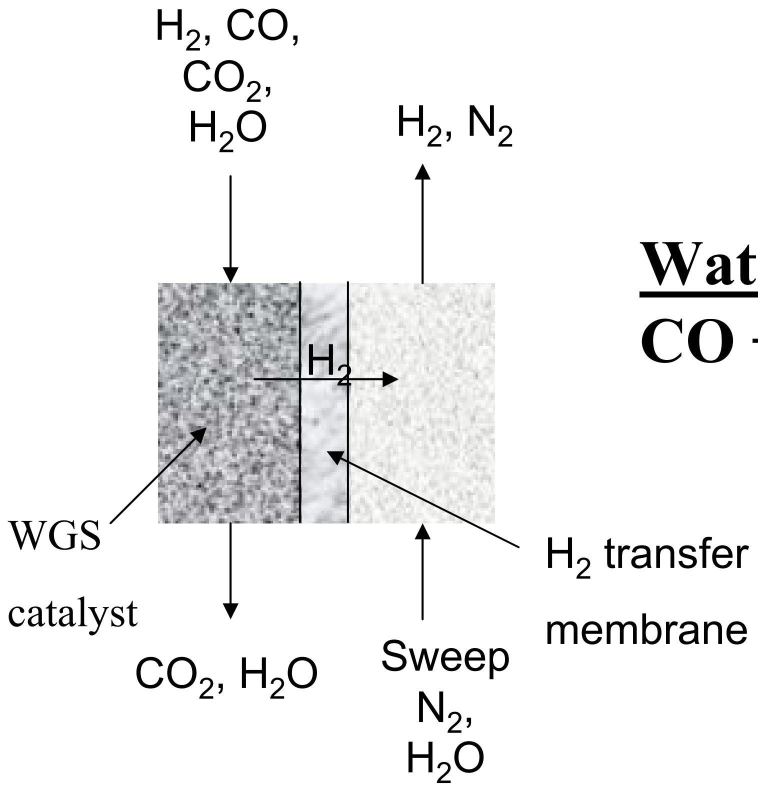
•Avoided and capture costs slightly lower than baseline in Case Study with very low costs (less than 15 $/ton).

• Capex reduction might be achieved by relaxing CO_2 recovery requirement.

Integration between WGS and CO_2 capture



MWGS Reactor Concept



Water gas shift

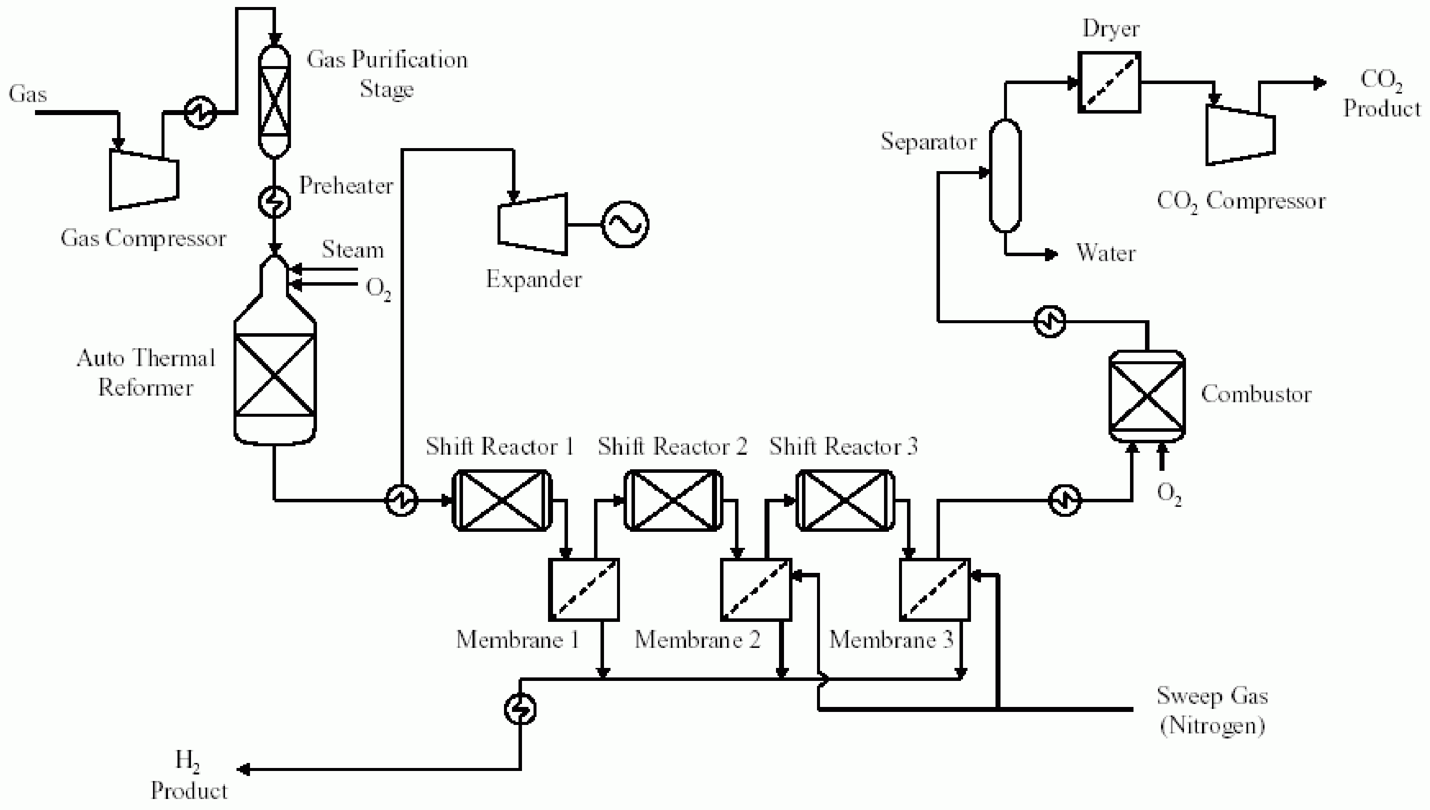
$CO + H2O \leftrightarrow CO2 + H2$

EU Grace MWGS Overview

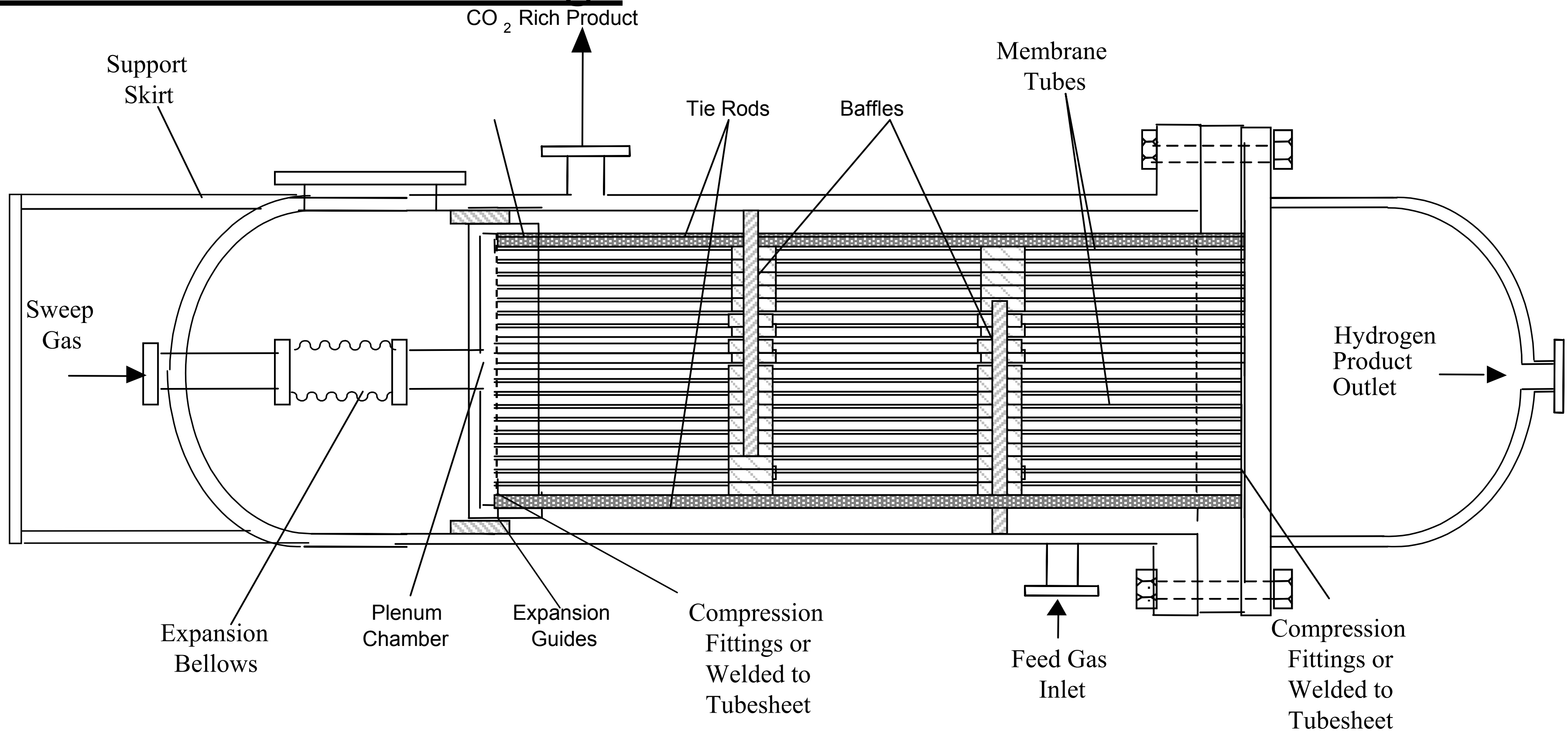
- Two year EU/CCP co-funded Project to develop a highly selective hydrogen membrane for a water gas shift reactor (BP, Norsk Hydro, SINTEF, Univ. Twente, KTH, Univ. Zaragoza, IRMERC).

- **Dense membrane - SINTEF**
  - 1-3 µm Pd/Ag alloy foil sputtered on single crystal silicon
  - Foil deposited on porous stainless steel support tubes
  - Tested at transmembrane pressure up to 15 bar
  - H_2 permeance up to $3 \cdot 10^{-6}$ mol/(m^2 s Pa) at 300ºC
  - N_2 permeation not detectable – perfect selectivity
  - Leak testing and repair technique developed

Proposed process scheme



Membrane Module Design



DOE MWGS Overview

- 12 month work period beginning 3/2002
- Four sulfur tolerant membrane development programs
  - Silica, ECN
  - Zeolite, University of Cinncinnati
  - Palladium alloy, CSM/TDA
  - Ceramic metal composite, Eltron
- Failure to develop sulfur tolerant membrane
  - Either inadequate H_2/CO_2 selectivity or intolerance to H_2S
- Membrane simulation model developed by ECN
- Eltron developed promising metal alloy membrane for sweet syngas

DOE MWGS Overview – Phase 2

- Eltron membrane development program
  - Focus on metal alloy membrane for <u>sweet</u> syngas
  - Significant improvement in flux/permeance
    - Two orders of magnitude improvement in flux over current state of the art (25 micron Pd)
  - Proof of concept testing successfully completed at ambient pressures
- SOFCo commercial MWGS reactor design
  - Innovative corrugated, planar design with stainless steel supports
  - Estimated costs is ~8% of the cost estimated in the Haldor Topsoe screening study for a 25 micron thick Pd membrane.

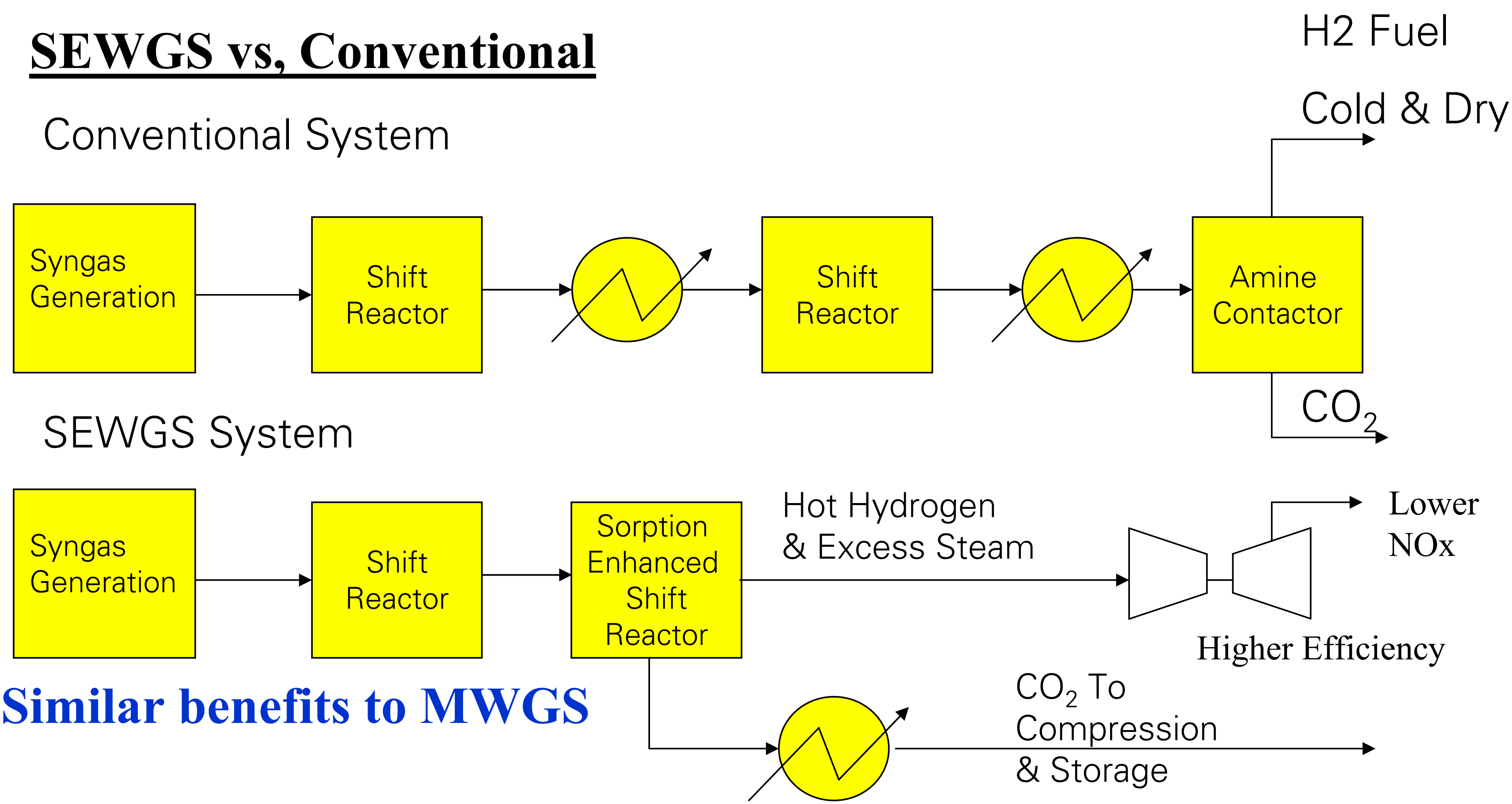
MWGS Conclusions

- Pre-Combustion Decarbonisation by Membrane Shift Reaction is technically feasible
    - Both Eltron and Sintef membranes look promising with 7-8 years estimated time to commercial demonstration.
- Sequential reaction/separation lower risk
- The efficiency of CO_2 capture for the process is higher then the baseline.
- Capital cost significantly lower than baseline.
- Cost of CO_2 avoided in the European Refinery case, significantly lower than baseline (- 35-40%).

Sorption Enhanced WGS Overview

- Technology under development by Air Products coupling WGS and CO_2 adsorption in a single vessel with cyclic regeneration for CO_2 recovery.
- Total Budget $1.2M (CCP/DOE)
- Test rig constructed
- Experimental programme run
    a. Adsorption tests
    b. Combined adsorption and reaction 'Proof-of-Concept'
- Capture schemes developed for Alaskan and Norwegian Case Studies.

SEWGS vs, Conventional



Similar benefits to MWGS

SEWGS main conclusions

- SEWGS Concept proven – CO slip dropped by about 80%.
- Avoided CO_2 Cost reductions based on achieved results in Norwegian Case > 40%.
- Overall efficiency from 56% to 48.2%.
- Technology relatively low risk & short timescale compared to membranes.
- NOx emission reductions possible to <25ppm
- Possible further savings by developing better adsorbents.
- Time to commercial demo estimated in 5-6 years.

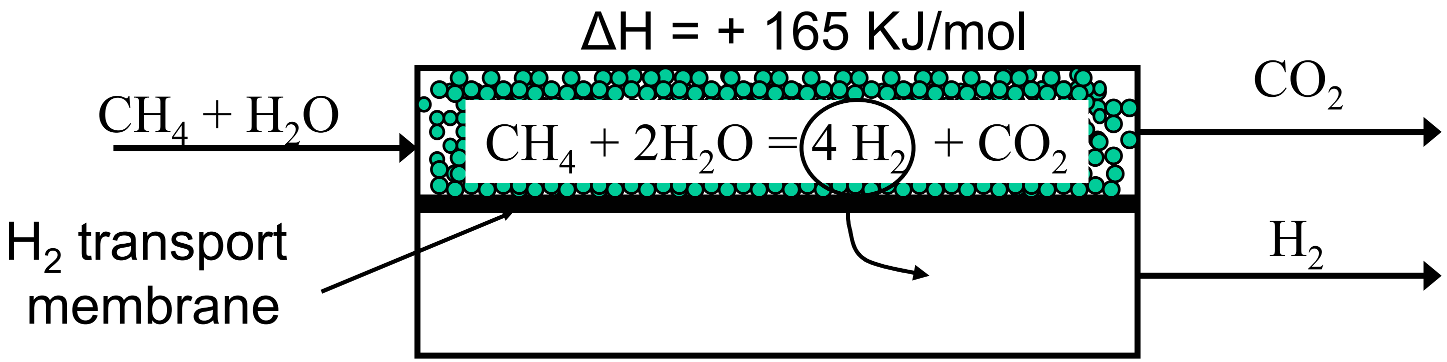
Hydrogen Membrane Reforming

- A 2.5 year and 1.9 mil US$ project funded by Klimatek (52%).
- Vendors: Norsk Hydro, Sintef and UiO
- Tasks:
  - ❖ Ceramic Conducting Materials
  - ❖ Reactor design
  - ❖ Process design
- Target:

Develop Mixed Conducting Membrane (MCM) with sufficient H_2 transport rates and stability under selected process conditions. Develop a techno-economically viable PCDC process including said materials.

Hydrogen Membrane Reformer: The Concept

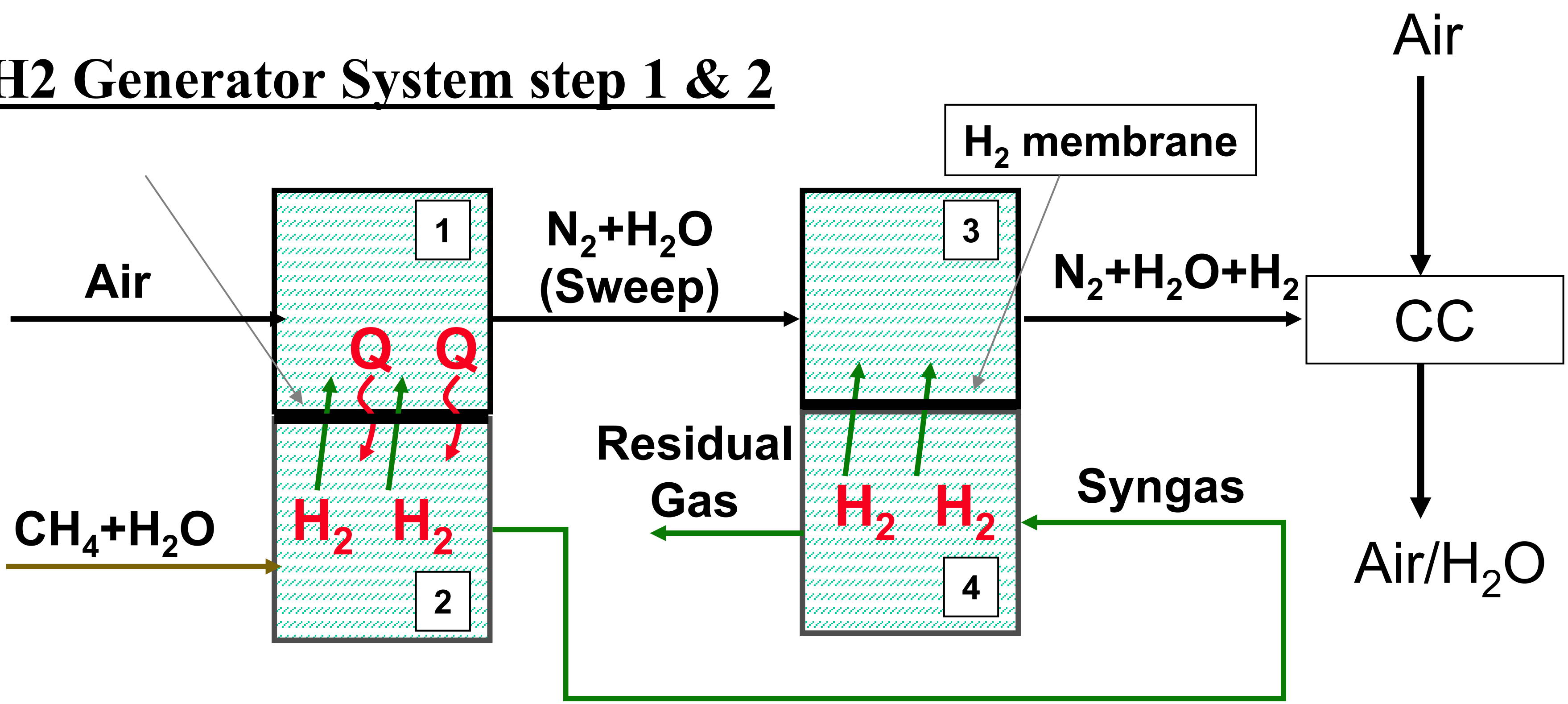
- **Combination of reforming reactor and separation**
- **Extract product gas (H_2) from reactor, no traditional CO_2 removal system required**
- **Drive equilibrium limited reactions towards completion**
- **Expand allowed range of temperatures and pressures**



Overall membrane performance

- Experiments/model predict hydrogen flux above target
  - Scatter not yet fully understood
- Model predicts stability in process above 750°C
  - May be further improved
- Excellent high temperature stability
  - melts at around 2000°C, sinters >1700°C
  - high temperature creep unlikely to limit life time
- Excellent stability at low oxygen partial pressure in H_2 and natural gas.

H2 Generator System step 1 & 2



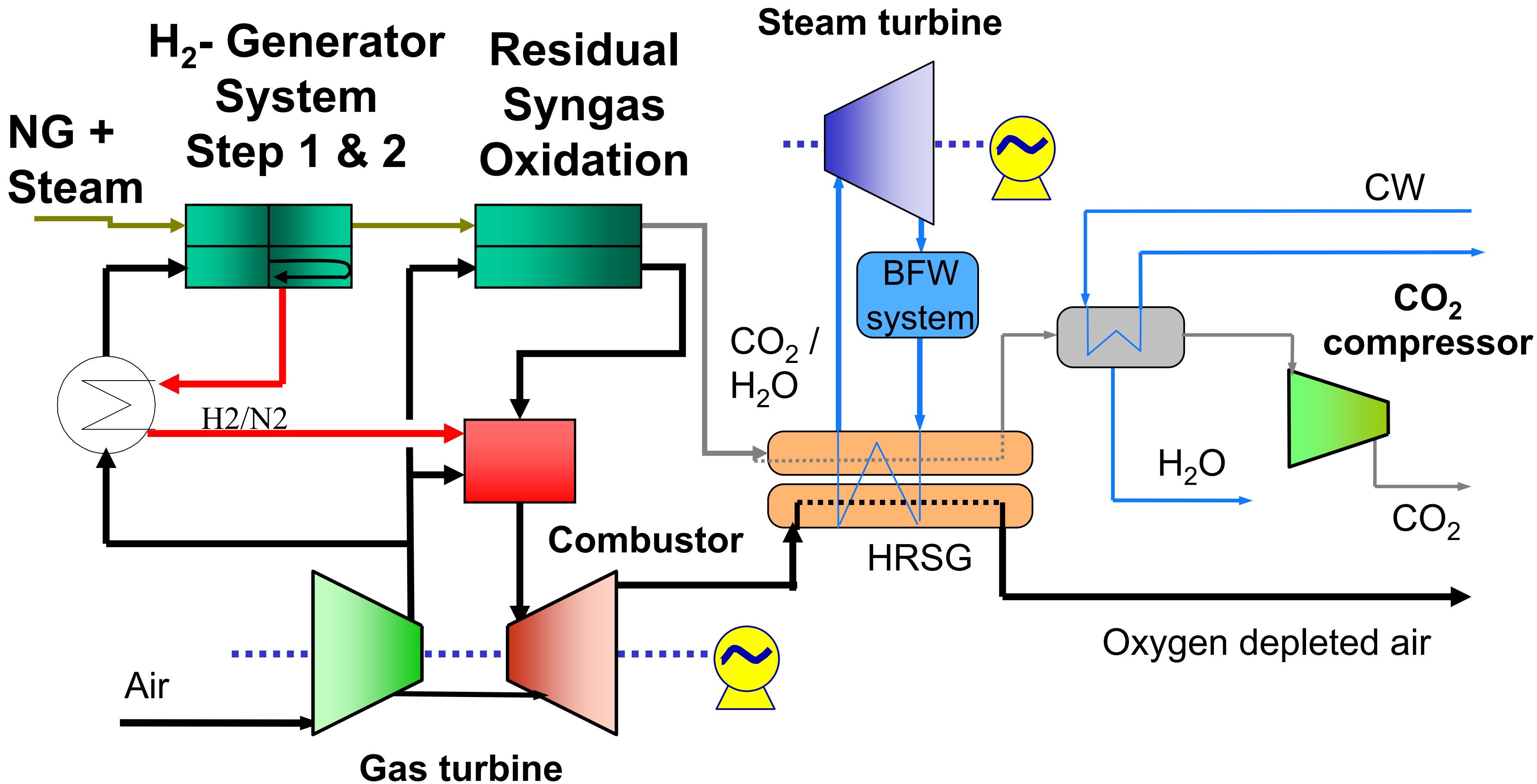
1 ½ $O_2+H_2 = H_2O$

3 Sweep

2 $CH_4+H_2O = CO+3H_2$
$CO + H_2O = CO_2+H_2$

4 $CH_4+H_2O = CO+3H_2$
$CO + H_2O = CO_2+H_2$

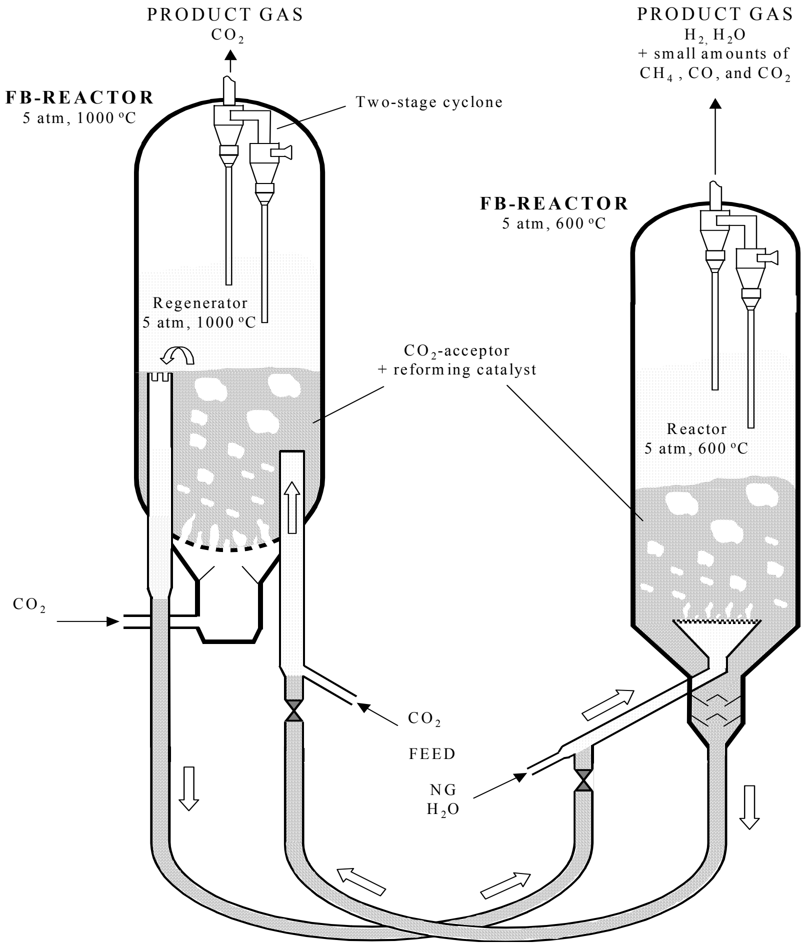
H2 Membrane Reformer - Power Plant



Process development summary

- Potential CO_2 capture cost reduction in CCGT by 50 % Vs Baseline.
- 5 ppm NOx emission can be achieved without catalytic NOx reduction.
- Loss in efficiency only 5%-points (vs. conv. CCGT).
- CO_2 emission close to zero.
- Compact Hydrogen Plant: Only 20 x 80 m (plot plan).
- Longer time (and costs) to market than other technologies. Pilot scale in operation by 2007-2008 and demo-unit by 2012-2013.

The IFE Concept: Complete Integration



Reforming:

$H_2O : CH_4 = 3.5 / 2$

$CaO : CH_4 = 1.5$

T = 600°C

p = 5 bar

Calcination:

T = 1000°C

p = 5 bar

Atmosphere = CO_2

IFE Conclusions

- 90% CO_2 removal is possible
- CCPP with electrical efficiency 58% (LHV) is reduced to 40 - 44%
  - IFE CO_2-capture concept is intended to operate at lower pressures, H_2-fuel has to be compressed
  - Need for sulphur removal
- Producing H_2 for a steam boiler, waste heat is also generated
  - Heat can be used for preheating the boiler

Due to very poor efficiency the team agreed not to pursue this concept further

PCDC Key Outcomes

- Advanced Pre-combustion technology offers significant long-term cost reduction opportunities and the possibility of hydrogen production with minimal associated CO_2 emissions;
  - Cost reductions of 55% over BAT at the start of the CCP
  - For situations where syngas must be produced for reasons other than carbon sequestration (for example to make H_2 or to produce power by IGCC), the incremental cost to capture CO_2 can be as low as $15/t."
  - Process step reduction and H_2 membranes offer significant capital cost reductions and further potential for reducing CO_2 avoided cost in the 2010-2015 perspective.