Project no. 019972 (SES6)

CACHET

Carbon Dioxide Capture and Hydrogen Production from Gaseous Fuels

Instrument type: Integrated Project

Priority name: Integrating and strengthening the European Research Area

DSP 5.3 Publishable Final Activity Report

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Project co-ordinator name: Jonathan Forsyth
Project co-ordinator organisation name: BP Exploration Operating Company Ltd (BP)

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1. Project Execution

Capture and storage of CO_2 with H_2 production is a large-scale option for long-term emissions reduction in Europe. Whilst some CO_2 capture technology integrated with H_2 production is available today the main barrier to its use is its high cost and lack of proper integration with H_2 based power production and high pressure, high purity vehicle fuel applications. The CACHET project is developing technologies to half the cost of CO_2 capture from natural gas with hydrogen production.

CACHET is a diverse consortium of research institutes, universities, energy businesses, engineering and manufacturing companies. Co-ordinated by BP with 28 participants from EU Member states and EU Acceding and Associated countries, USA, Canada, China and Brazil and is supported by the joint industry/government CO_2 Capture Project (CCP). The partners include

- Oil & Gas Companies – BP, Shell, ENI, Chevron, ConocoPhillips, Suncor, Petrobras, StatoilHydro
- Electricity Utility Companies – Endesa, E.ON, Electricity Authority of Cyprus
- Engineering, Plant and Equipment and Contractors – Siemens, PDC, Air Products, Technip, Alstom, Meggitt
- R&D Institutes – ECN, IFP, Fraunhofer Umsicht, IETU, Dalian Institute of Chemical Physics, Sintef, CSIC
- Universities – Technical University of Vienna, Technical University of Sofia, National Technical University of Athens, Chalmers University

CACHET is devoted to researching four promising technologies: Advanced steam methane reforming, Redox technologies, Metal membranes and Sorption enhanced water gas shift.

During the 3rd year of the CACHET project, the team has operated large scale experimental equipment taking significant steps towards scaling up these technologies. Progress relies on a strong integration between experimental and paper study, continuous economical and scenario development continue to maximise the chances of achieving commercial success.

IFP with support from the HyGenSys work pack partners, notably Technip have made significant strides in the detailed design of the HyGenSys reactor. While the reactor design is complex and challenging, IFP have considered the operational aspects of the technology. The 'cold mock-up' unit has proved a standard reformer catalyst can be consistently loaded and unloaded into the bayonet reformer tubes.

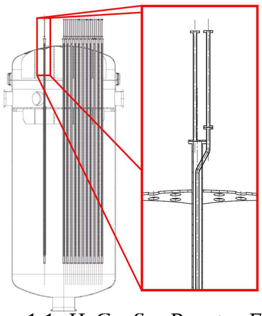

Figure 1.1: HyGenSys Reactor Exchanger Concept

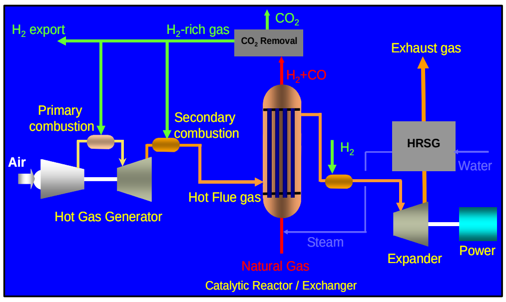

Figure 1.2: HyGenSys Concept

The reactor design is complex and critical to the success of the technology, IFP have selected a double pipe / bayonet tube concept. These will be mounted in a refractory walled and pressurised shell with the heat input from an externalized combustion chamber. The three train system will comprise of 8m diameter reactors each containing an estimated 300 tubes.

The initial 3 train HyGenSys concept showed a potential 78% CO_2 Capture ratio, and 44.5% efficiency, the low capture rate can be attribute to high methane slip. During the 3rd year, the team has developed an alternative configuration which increases the capture rate to over the 90% CACHET target. This has been achieved by replacing one of the HyGenSys reactors with an air-blown Autothermal reformer, downstream of the other two HyGenSys reactors. The Autothermal reformer performs the reforming steam methane reaction at a higher temperature, increasing the conversion of methane and producing additional hydrogen

Figure 1.3: Chalmers improved 300W unit

CACHET has explored the application of Chemical Looping to hydrogen production and power generation. Three distinct concepts are being developed; these include Chemical Looping Reforming ($CLR_{(s)}$), Chemical Looping Autothermal Reforming ($CLR_{(a)}$) and One Step Decarbonisation.

Particles based on iron, nickel and manganese oxides, as well as perovskites are being investigated. During continuous operation in 300 W and 500 W chemical-looping combustors several materials have shown excellent results. Several hundred hours of continuous operation have shown no degradation of particles. The syngas produced contains no methane and low stoichiometric ratios suitable for $CLR_{(a)}$ are possible. Economic evaluation of atmospheric pressure CLR(a) show the economics of the process to be challenges. Testing in a pressurized semi-batch and semi-continuous units has shown the kinetics to be enhanced, but also no apparent increase in carbon formation. The Technical University of Vienna has recently successfully operated the 120kW Chemical Looping test rig. This unit, constructed within the CLCGASPOWER EU project, is one of the worlds largest and will provide essential data on the scale up of chemical looping process. The unit has successfully operated with both nickel oxide and the cheap, natural mineral ilmenite

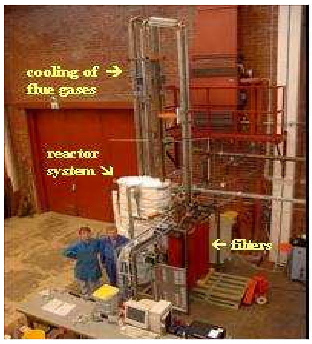

Figure 1.4: Chalmers 10kW

with some additional nickel oxide added to promote the rate limiting splitting of the methane.

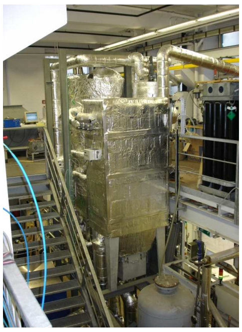

Figure 1.5: 120kW unit now operating at the Technical University of Vienna

One step decarbonisation continues to make progress with success in batch wise experimental work investigating operating conditions of the chemistry. After economic analysis, the focus of the project has been on testing the iron based material at higher pressures, to make the process economics more competitive, the results produced were better than expected.

Perovskite based materials have been produced and the initial screening process is completed. Several of the materials tested show a better performance than the reference material currently used in the One-Step hydrogen reactor.

Figure 1.6: 2 μm thick Pd/alloy membranes on porous stainless steel (PSS®) support produced by SINTEF

Sintef have built upon the work undertaken in the FP5 'Grace' project scaling up their palladium membrane on steel support technology from 2.5cm to 50cm long. Long term stability tests over 150 days at a temperatures from 325 - 400^{o}C, concludes the membrane lifetime would be between 2-5 years (<400 ^{o}C). Sintef's work has also shown that permeance is reduced by a factor of five for a synthesis gas mixture compared to a H_2/N_2 mixture. The decreased is due to hydrogen dilution, depletion and competitive adsorption of other components on the membrane surface.

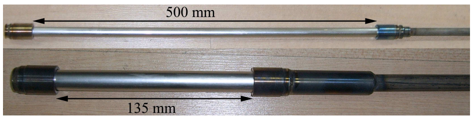

Figure 1.7: Pd membranes from DICP with ECN's high pressure, high temperature sealing.

Sintef's own testing has shown some promising results:

- H_2 flux upto 2477mL/cm^2/min @25bar DP, 400 ^{o}C
- High pressure H_2/N_2 permselectivity 3000 (@25bar DP, 400 ^{o}C)
- H_2 permeance up to 8x10^{-7} mol/m^2/s/Pa (WGS conditions)

Dalian have produced and tested their own electro-less plating on glazed ceramic supports. Permeability through 3-5μm membranes has been measured at >2x10^{-6} mol/m^{2}sPa (2.0MPa DP H_2) with a nonlinear pressure dependence of H_2 permeance (n~0.64) indicating external mass transfer limitations. 200 hour stability tests have produced constant 99.9% H_2 at 88.7% recovery rates at 400^{o}C.

Figure 1.8: ECN's test unit membrane reactor

ECN have designed and started construction of the membrane Process Development Unit (PDU). Multiple 50cm long tubes will be tested for both reforming and WGS to confirm the suitability of the membranes and the principles of hydrogen membrane reactors: 1) Parallel reaction + H_2 separation. 2) Equilibrium shift for high conversions. 3) WGS reaction at increased temperature. 4) Reforming at decreased temperature


Figure 1.9 SEWGS Multicolumn unit

Work on the Sorption Enhanced Water Gas Shift (SEWGS) single column unit was extended to include both adsorption and shift reaction using a simulated syngas feed and the principle of Sorption Enhanced Water Gas Shift was demonstrated. Year 2 also saw the construction and commissioning of the multi-column unit: six columns, each three times as tall as that in the single column. The unit is now fully operating and producing experimental data, simulating the full cyclic operation of the SEWGS system. The results from the single column unit have shown the steam requirements for rinse and purge are lower than expected. A model has been built to help understand the experimental data and optimise the cycle. The model is capable of matching the single column data accurately. The multicolumn data has been much more complex to analyse and calibrate a model to fit. While the multicolumn unit has proven the enhancement of the WGS reaction by separation of the carbon dioxide, some experimental observations are difficult to understand. There is clearly an opportunity for more experimental work and study to allow the high prospects of this technology to be realised. Some of the earlier experimental work suggested there may be some challenges with the lifetime of the hydrotalcite material as dusting became evident. A modified material showed some improvements and these can be expected to continue in the FP7 CAESAR follow on project.

The Optimisation and Integration team has evaluated the benefits of combining combinations of the technologies whose performance characteristics are complimentary and may be integrated to achieve more substantial economic benefits. Initially 55 combinations where identified of which 8 where believed to worthy of more detailed investigation. These included:

- HyGenSys – Sorption Enhanced Water Gas Shift (SEWGS)
- Chemical Looping Steam Reforming (CLR(s)) – Membrane Water Gas Shift (MWGS)
- One Step Decarbonisation (OSD) – Membrane
- OSD – Membrane – MWGS
- Chemical Looping Autothermal Refoming (CLR(a)) – SEWGS
- Integrated Membrane Reformer (MREF) – CLC
- MWGS – CLC
- CLR(a) – MWGS

All four of the CACHET technologies have been assessed from a Health, Safety and Environmental (HSE) and economic perspectives. IETU and Fraunhofer have concluded that all the HSE issues so far identified present no insurmountable barriers to the development of the technology. Good engineering and operational practises will facilitate safe long term operation.

The economics of each technology has been completed to incorporate the latest experimental data. Please see previous publications for a description of the economic assumptions and boundary conditions.

Figure 1.10 shows the results of the combination study, which suggest that although some combinations can improve the efficiency by up to 2.6% pts, the benefits are outweighed by the total capital cost increase.

Combined process	Process 1 [-]	Process 2 [-]	ΔEfficiency relative to Process 1 [%]	ΔEfficiency relative to Process 2 [%]	ΔProduction cost relative to Process 1 [€/MWh]	ΔProduction cost relative to Process 2 [€/MWh]	ΔCapitial cost relative to Process 1 [Mio€], TCI	ΔCapitial cost relative to Process 2 [Mio€], TCI
HyGenSys - SEWGS	HyGenSys	SEWGS	0,26	2,66	n. a.	n. a.	n. a.	n. a.
CLR-s - MWGS	CLR-s	MWGS	0,00	-0,02	1,4	10,6	2	62
OSD-Mem	CLR-a	OSD	0,04	0,03	-4,6	-0,6	48	-8
OSD - MWGS	OSD-Mem	MWGS	0,00	-0,01	1,2	14,5	12	157
CLR-a - SEWGS	CLR-a	SEWGS	-5,00	-3,60	16,7	25,9	49	203
MREF-CLC	MREF	CLC	0,10	n. a.	6,0	n. a.	88	n. a.
MWGS-CLC	MWGS	CLC	-0,90	n. a.	10,8	n. a.	149	n. a.
CLR-a - MWGS	CLR-a	MWGS	No detailed investigation - parameter studies reveal: obviously no economic alternative					

Figure 1.10: Changes in efficiency and costs when combining pairs of the program technologies

The consortium recognises the world's research communities continues to progress forward in this area of research developing CO_2 capture technologies. This workpack surveyed 1901 patents and 160 references, all post 2002 English language publications with the objective of defining and benchmarking novel CO_2 capture concepts technologies with the four CACHET technologies. Figure 1 shows the review process.

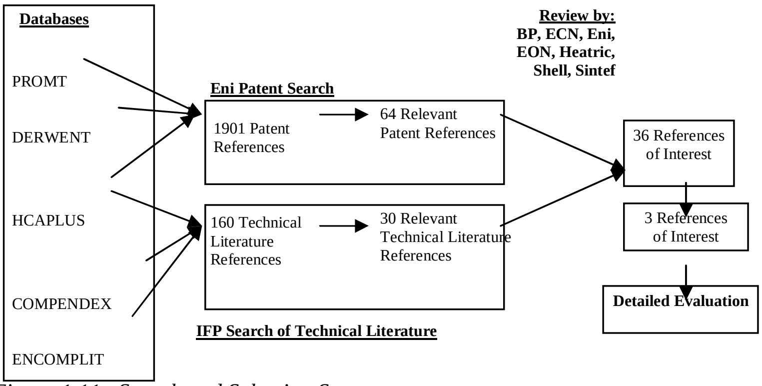

Figure 1.11. Search and Selection Strategy

Where the published data permitted, a more rigorous assessment was made on six selected technologies which appeared to be suitable for pre-combustion CO_2 capture from natural gas:

1. Sorption Enhanced Reforming
2. Alternative Chemical Looping concepts
3. Topchiev H_2 permeable membrane
4. High temperature proton conducting membranes
5. Microchannel reforming
6. CO_2 permeable membranes

The currently published data on CO_2 permeable membranes suggested that existing performance was insufficient to achieve the objectives. The assessment showed that Sorption Enhanced Reforming and High temperature proton conducting membranes and CO_2 permeable membranes all increased the energy efficiency beyond the CACHET base case, although none of these appeared to improve on the higher range of the efficiencies calculated for the CACHET technologies.

Dissemination has been a project highlight: the consortium acknowledges the importance of promoting the development of low carbon technologies. The Technical University of Athens have led the dissemination activities and our website (www.CACHETCO2.eu) has been continually updated with the latest articles and presentations.

After three years of intensive studies we have developed seven technologies each has a higher energy efficiency than the current state of the art. One technology (MWGS) reduces the cost

of carbon dioxide capture by >30%. Each technology has taken substantial steps to lowering the cost of CCS across Europe and the rest of the world.

	Reference	Base Case	HyGenSys	CLR(s)	CLR(a)	OSD	MemREF	MemWGS	SEWGS
Efficiency (%)	57.2	40.9	41.9	46.3	42.1	46.2	46.2	47.1	44.3
CACHET Target (49.05%)	49.05	49.05	49.05	49.05	49.05	49.05	49.05	49.05	49.05
Avoidance rate (%)	-	92.6	91	92	92.2	92.3	91.9	92.1	94.9
Capture rate (%)	-	94.8	93.4	93.5	94.3	93.8	93.5	93.5	96
CACHET Target (90% CO2 Avoided)	90	90	90	90	90	90	90	90	90
Cost of capture (€/t CO2)	-	82.1	77.1	81.5	101.2	88.1	96.1	65.9	75.9
Cost of avoidance (€/t CO2)	-	117.5	107.9	102.4	140.6	110.8	121.1	81.2	99.1
CACHET Target (€58.75/te)	58.75	58.75	58.75	58.75	58.75	58.75	58.75	58.75	58.75
Total fixed investment (€m)	194.9	461.8	587	562	586	534	530	476	468
Power output (MWe)	389.8	366	480	383	330	356	352	392	366.9
Break even electricity price (€/MWh)	55.9	86.6	82.7	81.3	94	84.2	87.4	74.4	81.3
Fixed Cost (€/MWh)	9	22	19.7	22.6	27.6	23.3	23.5	18.8	26.8
Variable Cost (€/MWh)	46.9	64.6	63	58.7	66.4	60.9	63.9	55.6	54.5
Specific Investment	0.50	1.26	1.22	1.47	1.78	1.50	1.51	1.21	1.28
CACHET Target (0.88 €M/Mwe)	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88

Figure:1.12 Economic summaries of the CACHET technologies

More information can be obtained by contacting the project manager (richard.beavis@uk.bp.com).

2. Dissemination and use

Exploitable Knowledge 1 (HyGenSys): Alternate Scheme with recirculation of nitrogen

This is an improvement of the original process scheme proposed by IFP to further improve efficiency and CO_2 capture rate fro the HyGenSys process scheme.

- Internally developed by IFP.
- It may be exploited indirectly through process licensing by IFP, and, more directly by the Engineering Contractor in charge of commercial plant design and construction, and by the end-user through lower costs for Capture.
- The following stage of research should be a pilot plant after CACHET (2010-2013).
- Possible collaboration with EPC Contractor firm
- Patent Application filed in 2006 by IFP (Patent number FR2900934 (A1)).

Patent **EP1854761A**: Method of producing electricity and a hydrogen-rich gas by steam reforming a hydrocarbon fraction with calorie input by in situ hydrogen

Abstract:

The invention describes a process of co-production of power and hydrogen rich gas by steam reforming of a hydrocarbon feed with heat provided by the combustion of hydrogen inside the reactor-exchanger of steam reforming.

First claim:

1. Process of production of synthesis gas by vaporeforming of a hydrocarbon feed (A) in a reactor of vaporeforming (R1), and electric co-production of power, in which the contribution of calories required by the reaction of vaporeforming is obtained by a combustion has hydrogen (5) dilutes by part of the effluents of combustion (11), the aforementioned combustion being carried out inside the reactor-exchanger (R1), the necessary air has the aforementioned combustion (1) has a pressure ranging between 0,4 and 4 MPa absolutes by means of the compressor (C1), and the effluent resulting of the aforesaid combustion (6) constituting the circuit of dilution, is for a part (7 becoming 11) recycles has the entry of the aforesaid engine exchanging so as to dilute hydrogen (5) and has to limit the oxygen content in the reactor-exchanger (R1) has a lower value has 10% molar, the other part (12) of the effluent of combustion being introduced into a post combustion chamber (CC1), flow resulting (13) from combustion has hydrogen (19) in the afterburning chamber (CC1) is slackened in a turbine (TD1) which partly provides energy necessary to the compressor (C1), and which actuates an alternator (AT1) ensuring the co-production of energy electric.

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Exploitable Knowledge 2-5 (HyGenSys): Novel Internals and Burners for heat exchanger and reactor in the HyGenSys technology

These innovations are parts of the novel reactor/exchanger, which is the core of the HyGenSys technology. They will be integral part of this key equipment unit.

- Internally developed by IFP, with Technip co-inventor for knowledge 5.
- It may be exploited indirectly through process licensing by IFP, and, more directly by the Equipment Vendor in charge of constructing the HyGenSys reactor, and by the end-user through lower costs for Capture. Burners may in principle have a wider application to other technologies.
- Possible collaboration with Equipment Vendors and EPC Contractors. Application to other technologies may be studied.
- The following stage of research should be the pilot plant after CACHET (2010-2013).
- Patent Applications for knowledge 2-4 filed in 2006/2007. (Patent numbers FR2913097 (A1) , FR2914396 (A1) and FR2918904 (A1)) . Patent Application for knowledge 5 filed in 2008.

Patent **WO07118950A**: Internal combustion exchanger reactor for endothermic reaction in fixed bed.

Abstract:

The invention relates to an exchanger reactor (1) comprising a containment (2) - means of distributing a load through a catalytic zone in fixed bed (10), - means (6) of collecting the effluent output from the catalytic zone (10), - means of heating the catalytic zone (10), in which said collection means (6) include ducts passing through the catalytic zone (10) from one side to the other, said ducts being distributed in the catalytic zone and inserted between the heating means, and in which the means of heating the catalytic zone are contained in claddings (8) partly immersed in the catalytic zone (10), the claddings (8) being open at one of their ends and closed at the other, the open end being fixed to an upper tubular plate (21) delimiting the collection chamber (19) located above the catalytic zone (10), said heating means comprising at least one combustion zone (13) located close to the catalytic zone, means of supplying said combustion zone (13) with an oxidising gaseous mix (15) and gas fuel (17), and means of evacuating the gas effluent output from combustion (14).

First claim:

1. Reactor exchanger (1) including/understanding: - an enclosure (2) - means of distribution of a feed through a fixed-bed catalytic zone (10), - means of collection (6)

of the effluent resulting from the catalytic zone (10), - means of heating of the catalytic zone (10), in which the aforementioned means of collection (6) comprise channels right through crossing the catalytic zone (10), the aforementioned channels having set out again in the catalytic zone and intercalate between the means of heating, and in which the means of heating of the catalytic zone are contained in sheaths (8) partly immerged in the catalytic zone (10), the sheaths (8) being open at one of their ends and closed at the other, the open end being fixed at a tubular plate higher (21) delimiting the room of collection (19) located above top of the catalytic zone (10), the aforementioned means of heating comprising at least a zone of combustion (13) located near the catalytic zone, of the means of feeding of the aforesaid the zone of combustion (13) in gas mixture oxidizing (15) and out of gaseous fuel (17), and of the means of evacuation of the gas effluent resulting from combustion (14).

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Exploitable Knowledge 6 (HyGenSys): New process for hydrogen production with CO_2 capture and recycling of unconverted methane.

This is an improvement of the original process scheme proposed by IFP to further improve CO_2 capture rate.

- Internally developed by IFP.
- It may be exploited indirectly through process licensing by IFP, and, more directly by the Engineering Contractor in charge of commercial plant design and construction, and by the end-user through lower costs for Capture.
- Possible collaboration with EPC contractor in the development and commercialization of the process.
- The following stage of research should be the pilot plant after CACHET.
- Patent Application filed in 2008 by IFP.

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Exploitable Knowledge 7 (Chemical Looping Reforming): Novel Oxygen Carriers for Chemical Looping Reforming

The availability of oxygen carriers with high activity, low cost and good fluidization properties is key to the success of this technology. Several materials were investigated and showed promising features. A Ni-based oxygen carrier material prepared by impregnation on alumina supports has been developed and tested for Chemical-Looping Reforming of methane showing high activity and good operating performance.

- Different particle production techniques are also under investigation.
- Developed by CSIC
- It may be exploited indirectly through licensing of catalyst manufacturing by owners and, more directly by the catalyst manufacturer and the end-user. Techno-Economic evaluations will assess actual prospects.
- The following stage of research should be application to the pilot plant after CACHET (2010-2013).
- Collaboration with commercial catalyst manufacturer is necessary to perform this task.
- Patent Applications filed in 2007 and 2008

The invention relates to an oxygen carrier obtained by means of impregnation, comprising a nickel oxide on a thermally modified commercial - alumina (Al_2O_3) substrate, as well as to the method for obtaining same. The oxygen carrier can be used for the indirect fluidised bed combustion of gas (methane, H_2, CO, H_2/CO) for the production of energy without CO_2 emission (chemical-looping combustion, CLC) and for the production of synthesis gas (H_2 and CO) or H_2 by partial oxidation of methane with inherent CO_2 capture in a fluidised bed (chemical-looping reforming, CLR).

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Exploitable Knowledge 8 (Chemical Looping Reforming): Novel Oxygen Carriers and combination of oxygen carriers for Chemical Looping Reforming

The availability of oxygen carriers with high activity, low cost and good fluidization properties is key to the success of this technology. Several materials were investigated and showed promising features. Some aspects of this knowledge is subject to a patent application by Chalmers, other areas of particle development knowledge have been published.

- Developed by Chalmers University of Technology, CSIC, Sintef
- It may be exploited indirectly through licensing of catalyst manufacturing by owners and, more directly by the catalyst manufacturer and the end-user. Techno-Economic evaluations will assess actual prospects.
- The following stage of research should be application to the pilot plant after CACHET scaling up production to batches up to 1 ton (2010-2012).
- Collaboration with commercial catalyst manufacturer is necessary to perform this task.
- For most carriers IP rights are published (see list of publications). One patent application was filed in 2009 by Chalmers University of Technology. Short description below:

Some results (outside the patent application) are described in two published articles
1) Shulman, A., Cleverstam, E., Mattisson, T., and Lyngfelt, A., Chemical – Looping with Oxygen Uncoupling using Mn/Mg-based Oxygen Carriers for Methane Combustion
2) Shulman, A., Cleverstam, E., Mattisson, T., and Lyngfelt, A., Manganese/Iron, Manganese /Nickel and Manganese /Silicon Oxides Used in Chemical – Looping With Oxygen Uncoupling (CLOU) for Combustion of Methane

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Exploitable Knowledge 9 (OSD): Novel Oxygen Carriers for One Step Decarbonization

The commercial scale availability of a solid oxygen carrier is a pre-requisite to develop a redox technology. A basic formulation of the carrier has been carefully studied in the performance and in the manufacturing procedure for pilot scale preparations (some hundreds kilos). Scale-up preparations and production techniques in collaboration with a manufacturer

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- It will be exploited indirectly by licensing to the manufacturer
- Second generation (modified) solid oxygen carrier has been modelled and prepared on the basis of economical evaluations
- Developed by ENI, SINTEF
- Collaboration with a commercial catalyst manufacturer able to scale-up production to 1 ton batches is needed.
- The following stage of research should be application to the bench scale plant after CACHET (2010-2013).
- IP rights are published.

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Exploitable Knowledge 10 (OSD): Novel Oxygen Carriers for One Step Decarbonization

Economic assessment by the manufacturer of the OxygenCarrierMaterial (OTM) according to the basic formulation and the basic production technique (dry-impregnation batch operated). Alternatively to shortcut production process to start the manufacturing process from pre-produced spinel-like support ,now available from alumina producers, but with negligible economic advantages. Trials to reduce the production cost by investigations of spry drying and freeze granulation techniques didn't allow to maintain the expected process performances because the superficial area of this so obtained OTM isn't adequate

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- Developed 59by ENI
- Mixed oxide active phase OTM based on hematite (Fe_2O_3) and ceria (CeO_2) formulated at various molar ratios are efficient oxygen carriers able to afford more oxygen to the OSD because the higher active phase loading and the stabilization of the di-valent iron due "in situ" formation of the Fe/Ce perovkite. This new OTM will be suitables in OSD at high pressure to prevent coke formation and incomplete combustion of the fuel (reforming)
- Developed by ENI & Sintef

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Exploitable Knowledge 11 (OSD): Novel Process Configuration for One Step Decarbonization

The membrane integration to the flameless combustion OSD process step allow us to extract partial oxidation products instead to combust them and as an alternative by introducing shift and PSA downstream steps afford interesting beneficial effects because: it is enhanced the amount of hydrogen produced and it is reduced the amount of compressed air in the hematatite regeneration step

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- Developed by PDC
- OSD process conditions can be properly modified by feeding a moderate excess of steam to the water-splitting reactor, this allow us to shift toward the products the splitting equilibrium and quantitatively to convert wuestite this has a beneficial effect on economics because: it is enhanced the cold gas efficiency of the process, this H_2/Steam output from WS will not need to be anymore diluted before the turbine combustion
- Developed by PDC
- An additional quote of NG can be fed to the gas turbine by-passing the OSD island, and so co-fed with the output H2/steam from WS, this allow us to improve the electrical efficiency of the H2(OSD)CC up 49% but in the same time to preserve the 95% level of CO2 capture.
- Developed by PDC

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Exploitable Knowledge 12 (Membrane Reforming and Water Gas Shift): Novel techniques for fabrication of thin film Pd-membranes

A leak-proof membrane element for the selective separation or cleaning of gas, wherein a metal foil (membrane) is deposited onto a supporting stock (substrate) having connection means on the ends/edges of the substrate allowing the membrane element to be installed in a housing. A metal foil having a thickness of less that 10 micrometers and being selectively permeable for specific gases, is arranged in flakes or wound with overlapping joints on the outside of the substrate any joints being welded together by diffusion bonding so that the foil forms a continuous, leak-proof metal membrane layer. The substrate being made of a material (metal, ceramic, polymer, or combinations thereof) exhibiting a very high gas flux for the gas(es) that the membrane is to let through.

- In the effort of scaling-up the membranes to sizes suitable for pilot plant modules (and later commercial units), novel fabrication techniques were developed with special reference to the sealing technology and the interaction between metal film and support.
- Developed by Sintef.
- It may be exploited indirectly through licensing of the membrane fabrication technique by owners and, more directly by the membrane manufacturer and the end-user. Techno-Economic evaluations will assess actual prospects.
- The following stage of research should be application to the pilot plant after CACHET(2010-2013)
- Possible collaboration with commercial membrane manufacturer.

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Exploitable Knowledge 13 (Membrane Reforming and Water Gas Shift): Novel types of reactor integrating membrane and catalyst

Integration of catalyst and membranes, as well as heat management required development of novel types of reactor

- Developed by PDC, ECN and Sintef
- It may be exploited indirectly through equipment licensing by owners and, more directly by end-user.
- The following stage of research should be application to the pilot plant after CACHET (2010-2013.
- Possible collaboration with equipment vendor and commercial membrane manufacturer.
- No patent applications filed

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Exploitable Knowledge 14, 16, 17, 18 (SEWGS): New cycles

Studies in CACHET have led to a number of potential improvements to the SEWGS cycles. These are currently being progressed through Air Products' IPR team with a view to patent.

- Developed by Air Products (with ECN, PDC and BP).
- It may be exploited indirectly through licensing of the technology by owners and, more directly by the Engineering Contractor and the end-user. Techno-Economic evaluations will assess actual prospects.
- The following stage of research should be application to the pilot plant after CACHET (2011-2013).

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Exploitable Knowledge 15 (SEWGS): New cycle with high pressure recovery of CO_2

This is a novel cycle in which no depressurisation steps are carried out and the CO_2 product is recovered at the SEWGS feed pressure. This vastly reduces the CO_2 compression power needed for sequestration/transport and reduces the number of reactor/adsorption vessels needed.

- Developed by Air Products (with ECN and PDC)
- It may be exploited indirectly through licensing of the technology by owners and, more directly by the Engineering Contractor and the end-user. Techno-Economic evaluations will assess actual prospects.
- The following stage of research should be application to the pilot plant after CACHET (2011-2014).
- Technical and economic evaluation has shown insufficient economic benefit to justify patenting this knowledge; therefore this knowledge will not be patented.

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Exploitable Knowledge 19 (Integration): Novel process schemes integrating two or more CACHET technologies

PDC studied additional potential deriving from integration of two or more CACHET technologies.

- Developed by PDC and Partners involved in the technologies considered.
- It may be exploited indirectly through licensing of the technology by owners and, more directly by the Engineering Contractor and the end-user. Techno-Economic evaluations will assess actual prospects.
- Possible collaboration with EPC contractors and equipment vendors.
- The following stage of research should be application to an integrated pilot plant after CACHET 2013-2015).
- No patent applications filed

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