Characteristics of Cycle Components for CO_2 Capture

Flavio J. Franco[1], Theo Mina[1], Gordon Woollatt[1], Mike Rost[2], Olav Bolland[3]
[1]ALSTOM (LE8 6LH,UK), [2]Siemens Power Generation (Germany),
[3]The Norwegian University of Science and Technology (NO-7491, Norway)

Abstract

Within the ENCAP Project – ENhanced CO_2 CAPture - the benchmarking of a number of novel power cycles with CO_2 capture was carried out. Some of these cycles show good efficiencies but the ultimate implementation of any of them in commercial power plants depends upon the feasibility, technical and economic, of their components. In this paper, the methodology used to evaluate the components and some results are described. It had two stages. The first stage was a first evaluation of all components, based on expert opinion, resulting basically in three classes of components, involving: 1) current engineering practices, 2) new engineering practices but not new scientific developments and 3) substantial scientific developments. The second stage, still in progress, is a more elaborate numerical analysis, leading to basic design concepts. One example cycle is discussed in this paper.

1. Introduction

The ENCAP Project – Enhanced CO_2 Capture is a European Union funded research project with more than twenty partners from industry and universities. Its objective is the investigation of technologies for power generation that would meet the target of at least 90% CO_2 capture rate and 50% CO_2 capture cost reduction. ENCAP focuses on pre-combustion and oxy-fuel types of cycles. Benchmarking of a number of novel gas turbine based power cycles with CO_2 capture was carried out in work package WP6.1. These are shown in Fig.1. The first four cycles on the left are natural gas (NG) oxy-fuel cycles, the following ten cycles are natural gas pre-combustion cycles, including different configurations of novel reforming reactors and/or selective membranes, and the last three are coal Integrated Gasification Combined Cycles with Chemical Absorption, with integrated Air Separation Unit and with Oxygen Transport Membrane respectively. For the meaning of other initials, please see Figs. 3 and 4.

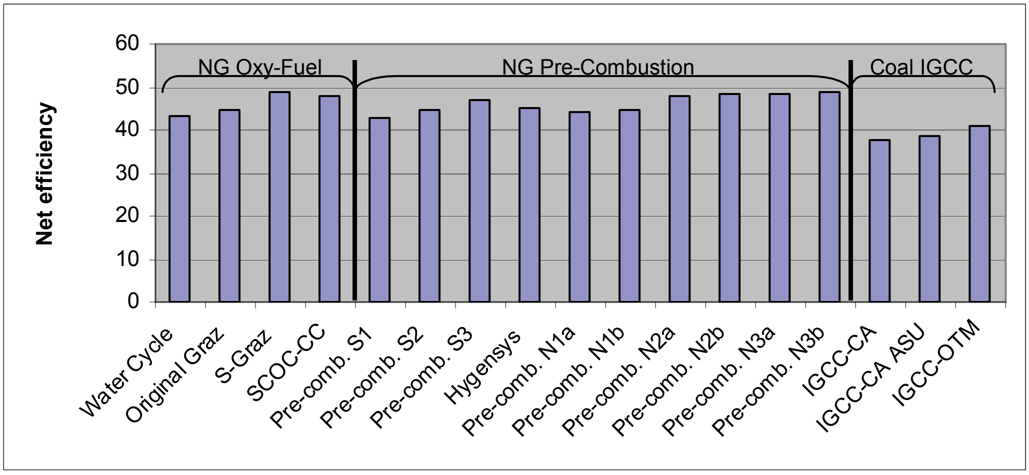


Fig. 1 – Efficiencies of the cycles studied in WP6.1

Work package WP6.2 of ENCAP has the objective of identifying the potential difficulties of practical implementation of these cycles in real world power plants, from the point of view of the equipment manufacturers. The ultimate practical implementation in power plants will depend upon attributes such as capital cost, efficiency, reliability, availability, maintainability and life expectancy. These attributes of the whole electricity generation system will depend on the corresponding attributes of its components: compressors, turbines, combustors, heat exchangers and novel components. The mission is thus to examine the components of those cycles and to evaluate them with respect to those attributes. If it is assumed that each cycle has on average five critical components, the task would involve around one hundred components. As a detailed study of all components would not be practical within a reasonable timescale, a two-stage approach was adopted.

In the first stage, a so-called 'component book' was created, containing some basic information for each component:

- Inlet conditions: streams, compositions, mass flows, pressures and temperatures
- Power, polytropic and isentropic efficiencies
- Outlet conditions: streams, compositions, mass flows, pressures and temperatures

Expert opinion was then sought about the critical components, covering materials, gas turbines with or without cooling, compressors, combustors, steam turbines, heat exchangers and special reactors. The components were classified into three levels, technically and economically, as shown in Table 1. In the second stage, more detailed numerical analysis was made of selected components from the most promising cycles studied in WP6.1 - at this point in the project, turbo-machinery components and combustors. It would not be appropriate to report the whole set of data and results produced in the ENCAP project. So, only the summary charts of stage one and one example including the analyses of stages one and two are presented in sections 2 and 3.

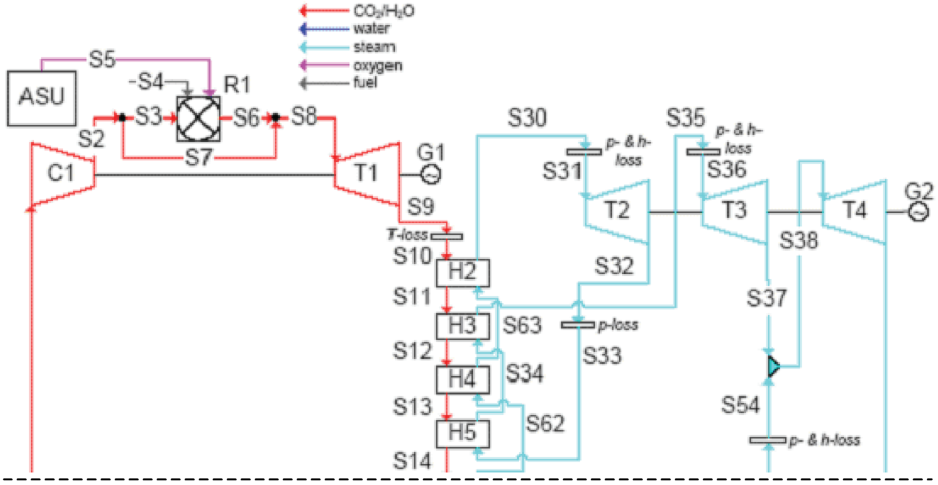
Table 1 - Classification of components according to expert opinion

Class	Technical evaluation	Economic evaluation
Green	commercially available or current engineering practice	usual costs of commercially available equipment
Yellow	new engineering practices but not new significant scientific developments	cost of new design or high capital costs due to size, quantity or special materials
Red	considerable scientific developments and new engineering practices	high development costs, high capital cost and/or high operation and maintenance costs

2. The 'Component Book'

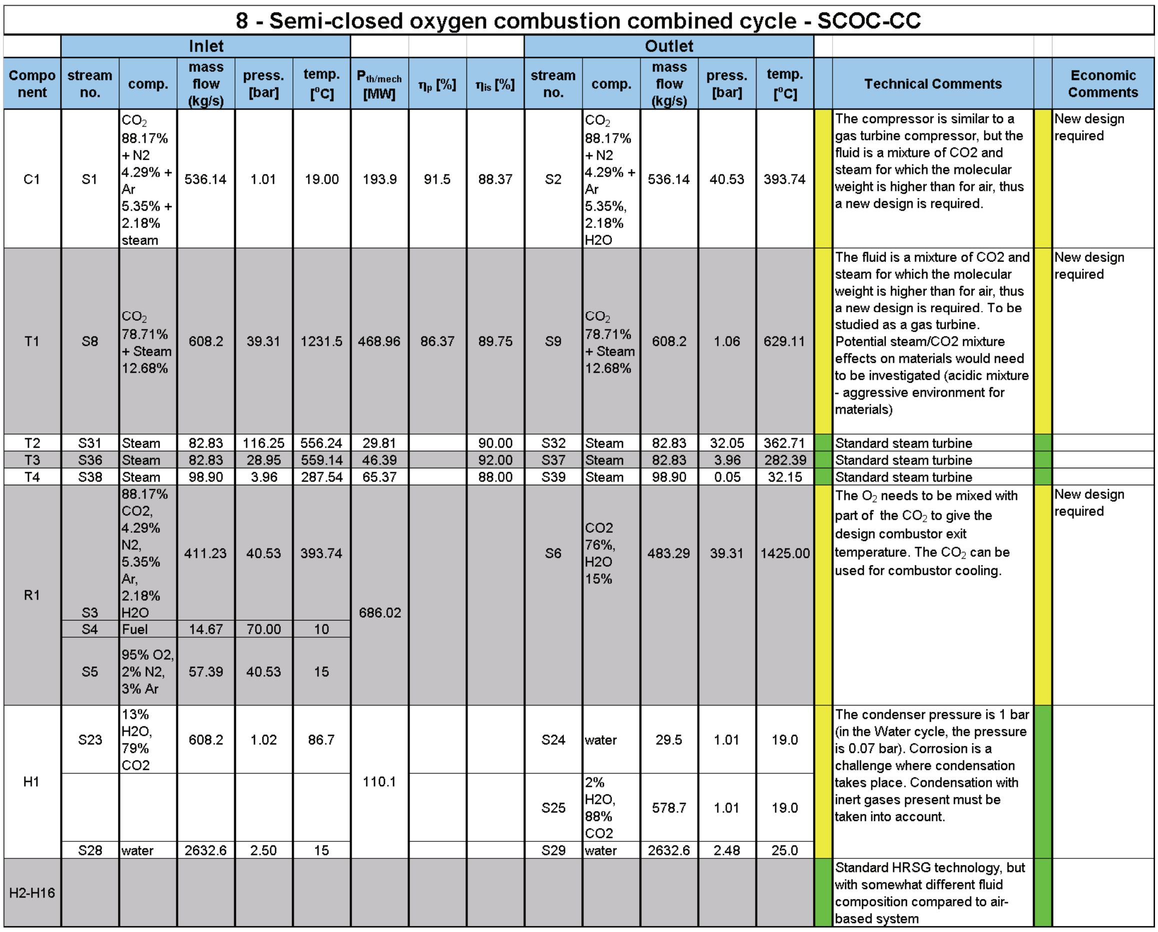
Initially the example of the Semi-Closed Oxy-Fuel Combustion Combined Cycle (SCOC-CC) will be discussed. Its flow diagram is shown in Fig. 2 and its individual evaluation sheet is shown in Fig. 3.

Basically, the main difficulties of this cycle result from the combustion process and from the working fluid in the compressor and in the gas turbine. The compressor and the turbine require a new design because of the working fluid, but it is unlikely that new scientific developments will be necessary. About the combustor, re-circulation of CO_2 is necessary, so that a design exit temperature is achieved and combustor cooling is made with CO_2. Also the starting transient process should be studied in a laboratory first and then in large scale. Considering the need for re-circulation and the transient regime, where combustion starts with air, moving slowly to oxygen with re-circulation, a new control system should be developed. However, all these developments, though outside the current engineering practices, do not include considerable scientific new developments. Finally, with regard to heat exchangers, low pressures are considered but they are not as low as the pressures of the Water Cycle.



partly shown for space reasons - heat exchangers H1 and H6-H16 not shown - ASU = Air Separation Unit

Fig. 2 – The Semi-Closed Oxy-Fuel Combustion Combined Cycle



8 - Semi-closed oxygen combustion combined cycle - SCOC-CC

	Inlet								Outlet								
Component	**stream no.**	**comp.**	**mass flow (kg/s)**	**press. [bar]**	**temp. [°C]**	**$P_{th/mech}$ [MW]**	**η_p [%]**	**η_{is} [%]**	**stream no.**	**comp.**	**mass flow (kg/s)**	**press. [bar]**	**temp. [°C]**		**Technical Comments**		**Economic Comments**
C1	S1	CO_2 88.17% + N2 4.29% + Ar 5.35% + 2.18% steam	536.14	1.01	19.00	193.9	91.5	88.37	S2	CO_2 88.17% + N2 4.29% + Ar 5.35%, 2.18% H2O	536.14	40.53	393.74	🟨	The compressor is similar to a gas turbine compressor, but the fluid is a mixture of CO2 and steam for which the molecular weight is higher than for air, thus a new design is required.	🟨	New design required
T1	S8	CO_2 78.71% + Steam 12.68%	608.2	39.31	1231.5	468.96	86.37	89.75	S9	CO_2 78.71% + Steam 12.68%	608.2	1.06	629.11	🟨	The fluid is a mixture of CO2 and steam for which the molecular weight is higher than for air, thus a new design is required. To be studied as a gas turbine. Potential steam/CO2 mixture effects on materials would need to be investigated (acidic mixture - aggressive environment for materials)	🟨	New design required
T2	S31	Steam	82.83	116.25	556.24	29.81		90.00	S32	Steam	82.83	32.05	362.71	🟩	Standard steam turbine	🟩	
T3	S36	Steam	82.83	28.95	559.14	46.39		92.00	S37	Steam	82.83	3.96	282.39	🟩	Standard steam turbine	🟩	
T4	S38	Steam	98.90	3.96	287.54	65.37		88.00	S39	Steam	98.90	0.05	32.15	🟩	Standard steam turbine	🟩	
R1	S3	88.17% CO2, 4.29% N2, 5.35% Ar, 2.18% H2O	411.23	40.53	393.74	686.02			S6	CO2 76%, H2O 15%	483.29	39.31	1425.00	🟨	The O_2 needs to be mixed with part of the CO_2 to give the design combustor exit temperature. The CO_2 can be used for combustor cooling.	🟨	New design required
	S4	Fuel	14.67	70.00	10												
	S5	95% O2, 2% N2, 3% Ar	57.39	40.53	15												
H1	S23	13% H2O, 79% CO2	608.2	1.02	86.7	110.1			S24	water	29.5	1.01	19.0	🟨	The condenser pressure is 1 bar (in the Water cycle, the pressure is 0.07 bar). Corrosion is a challenge where condensation takes place. Condensation with inert gases present must be taken into account.	🟩	
									S25	2% H2O, 88% CO2	578.7	1.01	19.0				
	S28	water	2632.6	2.50	15				S29	water	2632.6	2.48	25.0				
H2-H16														🟩	Standard HRSG technology, but with somewhat different fluid composition compared to air-based system	🟩	

Fig. 3 – Evaluation sheet of the Semi-Closed Oxy-Fuel Combustion Combined Cycle

General type of component	Oxy-fuel Water Cycle		Oxy-fuel Original Graz Cycle		Oxy-fuel Steam Graz Cycle		Oxy-fuel SCOC-GT		Oxy-fuel SCOC-CC		Pre-Combustion Siemens 1	
	4		5		6		7		8		9	
	Tech	Eco	Tech	Eco	Tech	Eco	Tech	Eco	Tech	Eco	Tech	Eco
Compressors			Very high volume flow rate (860 m^3/s). Potential corrosion problems. Unknown corrosion effects of CO_2 and steam in the cycle concentrations.	Two units in parallel required. Complex design.	CO2 + Steam. Potential corrosion problems.	Cost of materials development.	Mixture of CO2 and Steam. Potential corrosion.	New design due to properties of CO2.	Working fluid is a mixture of CO2 and Steam.	New design due to working fluid.	Large fractions of CO2 and steam. Potential effects on materials.	New design due to working fluid.
	🟩	🟩	🟨	🟥	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Turbines	Very high pressure ratio = 138. Potential sealing problems. Steam cooling. Turbine inlet temperature is 1254 °C after mixing with coolant. Working fluid is 87% steam + 12% CO_2.	Completely new design due to working fluid and pressure ratio.	Steam cooling. CO2 + Steam. Potential corrosion problems with inlet temperature 1247 °C.	High power output (470 MW). High development costs.	Slow pressure uncooled turbine for 10% CO2 and 89% steam. Exit gas below dew point temperature (32.54 °C). Corrosion potential problems.	Completely new design due to working fluid.	Mixture of CO2 and Steam. Potential corrosion.	New design due to working fluid.	Mixture of CO2 = Steam. Corrosion to be investigated.	New design due to working fluid.		
	🟨	🟥	🟨	🟥	🟥	🟥	🟨	🟨	🟨	🟨	🟩	🟩
Combustors and Other Reactors	High pressure (92 bar). Extensive development required. Desired temperature may be achieved by mixing steam to O_2.	High development cost.	Need to cool combustor with water & ex. gas.	Some cooling development cost.	Steam to be added for temperature control.	Cost of development of cooling system.	O2 to be mixed with CO2 for combustor temperature.	New design for CO2 circulation.	O2 to be mixed with CO2 for combustor temperature.	New design due to circulation.	Syngas splitting with H2 permeable membrane.	High development cost and unknown capital cost. Unknown reliability and effectiveness.
	🟥	🟥	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟥
Heat Exchangers	Very low pressure. Low heat transfer coefficient.	Large size equipment: high capital cost.			Low pressure condenser for CO2 & steam. Corrosion in condensation section.	Very low heat transfer coefficient.Exit pressure very low. Large size and capital cost.	Corrosion may be a problem in condensation section.		Corrosion may be a problem.		High temperature / multiple media.	Development costs and capital cost.
	🟨	🟥	🟩	🟩	🟨	🟥	🟨	🟩	🟨	🟩	🟥	🟥

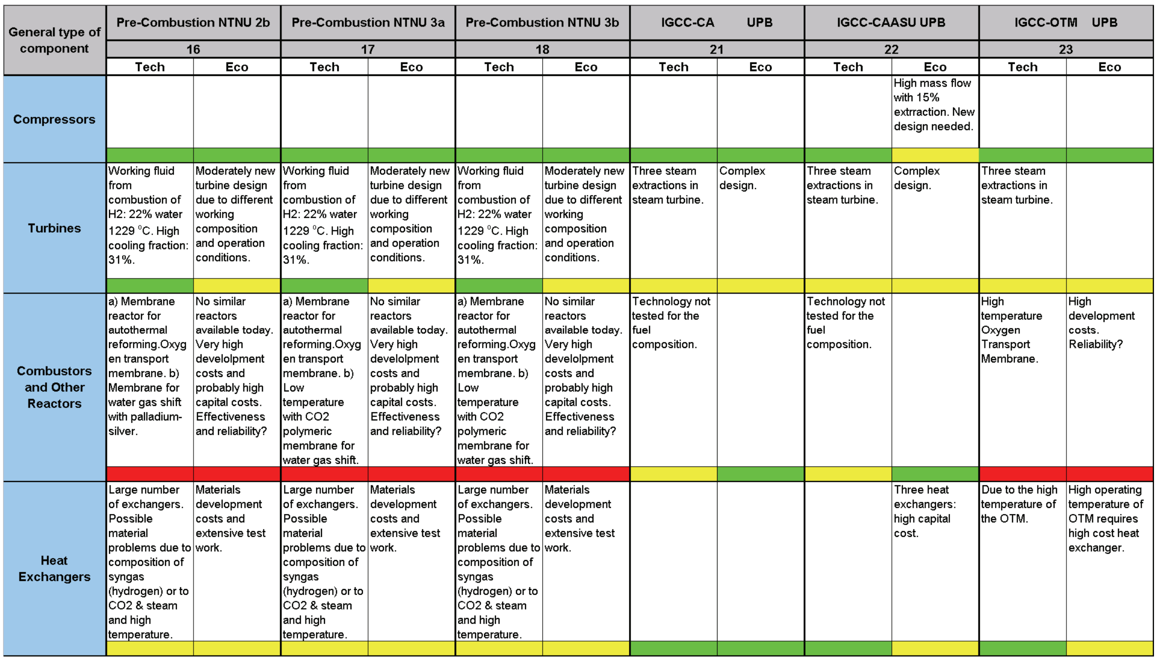
SCOC=Semi-Closed Oxy-fuel Combustion, GT=Gas Turbine, CC=Combined Cycle

Fig. 4.a - Summary of evaluation of components of all cycles studied

General type of component	Pre-Combustion Siemens 2		Pre-Combustion Siemens 3		Pre-Combustion IFP Hygensys		Pre-Combustion NTNU 1a		Pre-Combustion NTNU 1b		Pre-Combustion NTNU 2a	
	10		11		12		13		14		15	
	Tech	Eco	Tech	Eco	Tech	Eco	Tech	Eco	Tech	Eco	Tech	Eco
Compressors	Three-stage compressor with intercooling.	Capital cost.	Three-stage compressor with intercooling.	Capital cost.			74% H2 and 26% steam working fluid: possible material embrittlement problems.	Cost in materials developments.	74% H2 and 26% steam working fluid: possible material embrittlement problems.	Cost in materials developments.		
	🟨	🟨	🟨	🟨	🟩	🟩	🟨	🟨	🟨	🟨	🟩	🟩
Turbines					Air with large fraction of steam. Cooling to be considered.	Develolpment costs. High capital cost?	Working fluid from combustion of H2: 22% water 1229 °C. High cooling fraction: 31%.	Moderately new turbine design due to different working composition and operation conditions.	Working fluid from combustion of H2: 22% water 1229 °C. High cooling fraction: 31%.	Moderately new turbine design due to different working composition and operation conditions.	Working fluid from combustion of H2: 22% water 1229 °C. High cooling fraction: 31%.	Moderately new turbine design due to different working composition and operation conditions.
	🟩	🟩	🟩	🟩	🟨	🟨	🟩	🟨	🟩	🟨	🟩	🟨
Combustors and Other Reactors	Syngas splitting with H2 permeable membrane	Development costs, reliability, effectiveness.	Syngas splitting with H2 permeable membrane	Development costs, reliability, effectiveness.	High flame speed for pre-mixed system, leading to 2480 °C. Fuel dilution with steam and combustor cooling with steam needed.	Develolpment costs.	a) Membrane reactor for autothermal reforming. b) Membrane for water gas shift with palladium-silver. c) Membrane combustor to convert CH4, CO and H2 from WGS membrane to CO2 and H2O.	No similar reactors available today. Very high develolpment costs and probably high capital costs. Effectiveness and reliability?	a) Membrane reactor for autothermal reforming. b) Membrane for water gas shift with palladium-silver. c) Membrane combustor to convert CH4, CO and H2 from WGS membrane to CO2 and H2O.	No similar reactors available today. Very high develolpment costs and probably high capital costs. Effectiveness and reliability?	a) Membrane reactor for autothermal reforming. b) Membrane for water gas shift with palladium-silver. c) Membrane combustor to convert CH4, CO and H2 from WGS membrane to CO2 and H2O. Very high temperatures.	No similar reactors available today. Very high develolpment costs and probably high capital costs. Effectiveness and reliability?
	🟥	🟥	🟥	🟥	🟥	🟨	🟥	🟥	🟥	🟥	🟥	🟥
Heat Exchangers	High temperature / multiple media.	Development costs and capital cost.	High temperature / multiple media.	Development costs and capital cost.			Large number of exchangers. Possible material problems due to composition of syngas (hydrogen) or to CO2 & steam and high temperature.	Materials development costs and extensive test work.	Large number of exchangers. Possible material problems due to composition of syngas (hydrogen) or to CO2 & steam and high temperature.	Materials development costs and extensive test work.	Large number of exchangers. Possible material problems due to composition of syngas (hydrogen) or to CO2 & steam and high temperature.	Materials development costs and extensive test work.
	🟥	🟥	🟥	🟥	🟩	🟩	🟨	🟨	🟨	🟨	🟨	🟨

NTNU = Norwegian University of Science and Technology, IFP = Institut Francais du Petrole

Fig. 4.b - Summary of evaluation of components of all cycles studied



General type of component	Pre-Combustion NTNU 2b		Pre-Combustion NTNU 3a		Pre-Combustion NTNU 3b		IGCC-CA UPB		IGCC-CAASU UPB		IGCC-OTM UPB	
	16		17		18		21		22		23	
	Tech	Eco	Tech	Eco	Tech	Eco	Tech	Eco	Tech	Eco	Tech	Eco
Compressors										High mass flow with 15% extrraction. New design needed.		
	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟨	🟩	🟩
Turbines	Working fluid from combustion of H2: 22% water 1229 °C. High cooling fraction: 31%.	Moderately new turbine design due to different working composition and operation conditions.	Working fluid from combustion of H2: 22% water 1229 °C. High cooling fraction: 31%.	Moderately new turbine design due to different working composition and operation conditions.	Working fluid from combustion of H2: 22% water 1229 °C. High cooling fraction: 31%.	Moderately new turbine design due to different working composition and operation conditions.	Three steam extractions in steam turbine.	Complex design.	Three steam extractions in steam turbine.	Complex design.	Three steam extractions in steam turbine.	
	🟩	🟨	🟩	🟨	🟩	🟨	🟨	🟨	🟨	🟨	🟨	🟨
Combustors and Other Reactors	a) Membrane reactor for autothermal reforming.Oxygen transport membrane. b) Membrane for water gas shift with palladium-silver.	No similar reactors available today. Very high develolpment costs and probably high capital costs. Effectiveness and reliability?	a) Membrane reactor for autothermal reforming.Oxygen transport membrane. b) Low temperature with CO2 polymeric membrane for water gas shift.	No similar reactors available today. Very high develolpment costs and probably high capital costs. Effectiveness and reliability?	a) Membrane reactor for autothermal reforming.Oxygen transport membrane. b) Low temperature with CO2 polymeric membrane for water gas shift.	No similar reactors available today. Very high develolpment costs and probably high capital costs. Effectiveness and reliability?	Technology not tested for the fuel composition.		Technology not tested for the fuel composition.		High temperature Oxygen Transport Membrane.	High development costs. Reliability?
	🟥	🟥	🟥	🟥	🟥	🟥	🟨	🟩	🟨	🟩	🟥	🟥
Heat Exchangers	Large number of exchangers. Possible material problems due to composition of syngas (hydrogen) or to CO2 & steam and high temperature.	Materials development costs and extensive test work.	Large number of exchangers. Possible material problems due to composition of syngas (hydrogen) or to CO2 & steam and high temperature.	Materials development costs and extensive test work.	Large number of exchangers. Possible material problems due to composition of syngas (hydrogen) or to CO2 & steam and high temperature.	Materials development costs and extensive test work.				Three heat exchangers: high capital cost.	Due to the high temperature of the OTM.	High operating temperature of OTM requires high cost heat exchanger.
	🟨	🟨	🟨	🟨	🟨	🟨	🟩	🟩	🟩	🟨	🟩	🟨

UPB = University of Paderborn, IGCC=Integrated Gasification Combined Cycle, CA=Chemical Absorption, ASU=Air Separation Unit, OTM=Oxygen Transport Membrane

Fig. 4.c – Summary of evaluation of components of all cycles studied

These necessary technical developments are reflected in the costs. The concern about costs is moderate as new designs are necessary for compressor, turbine and combustor, but no scientific investigations seem to be required. As a consequence of these findings, no 'red' components are seen in the evaluation sheet of this cycle (Fig. 3).

The summary evaluation sheets shown in Fig. 4, obtained from all detailed individual sheets made for all cycles, are self-explanatory.

3. The Semi-Closed Oxy-Fuel Combustion Combined Cycle (SCOC-CC)

Considering the good position of the SCOC-CC cycle in the overall comparison made within WP6.1 and the absence of great challenges in the first-stage evaluation of components, a more detailed numerical analysis – second stage analysis - was made of some of these components. Highlights are given here about the compressor and the combustor.

Compressor

The gas in the SCOC-CC compressor is largely carbon dioxide. Compared to air, the gas has significantly lower values of both the gas constant and the ratio of specific heats. It can be shown that to achieve dynamic similarity with an air compressor, the 'CO2' compressor should run with approximately a 25% reduction in the blade tip speed and a 15% increase in the mass flow. In this cycle the rotational speed is 3000 rpm, i.e. the same value as that of existing 50 Hz power generation gas turbine compressors, while the mass flow is lower than that of typical heavy-duty compressors. Hence the diameter of the SCOC-CC compressor has to be reduced as compared to a compressor running with air in order to reduce the blade speed and the associated Mach numbers.

Further the pressure ratio of 40.13 is higher than that of current power generation gas turbines. At this high exit pressure the density of the gas is significantly higher than air. Hence in order to achieve a reasonable hub/tip ratio of the exit stage (to avoid large clearance losses) either the flow coefficient (axial velocity/blade speed) or the mean radius has to be reduced. If it is assumed that flow coefficients should not be reduced below a certain level, then the mean radius at the exit must be lower than in a conventional gas turbine compressor. The lower radius means that for a given limiting level of work coefficient (stage enthalpy rise over blade speed squared) more stages are required for a compressor using CO2.

As a first step in defining the compressor a parametric study was carried out on the first stage in isolation. An ALSTOM in-house code was run over a range of inlet guide vane exit angles, mean radii, flow coefficients and work coefficients. Having defined the first stage, candidate compressors were investigated. It was found that around 24 stages were required to achieve a pressure ratio of 40 in order to stay within conservative limits of work coefficient. A parametric study was then carried out over a range of mean radii, flow coefficients and work coefficients for the last stage. Distributions of the above were assumed for each stage through the compressor. The code was then run to the required pressure ratio adjusting the level of the stage work coefficients. After several calculations involving considerations of losses associated to blade tip clearances and of surge margin, a configuration was selected with 24 stages and the following last stage mean line parameters: radius = 0.64 m, flow coefficient = 0.45 and work coefficient = 0.25. A schematic view of the blade path of the final conceptual design is shown in Fig. 5 and the relevant parameters are given in table 2.

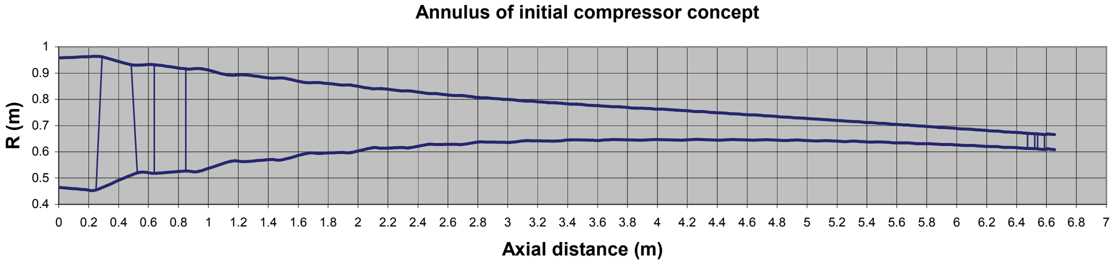


Fig. 5 – Compressor profile

Table 2 - Compressor calculated parameters

Number of stages	24	Rotor 1 hub Mach number	.841
Rotor 1 hub/tip ratio	.473	Stator 1 hub Mach number	.819
Rotor 24 hub/tip ratio	.915	Exit Mach number	.221
Rotor 1 tip Mach number	1.17	Length (m)	6.654

The working fluid of the SCOC-CC compressor necessitates the design of a radically different compressor from those currently in use in 50Hz power generation gas turbines and requires more stages at lower exit radius. The longer and slender rotor may result in rotor dynamics problems. Ways of reducing the overall length should be investigated. If the parameters are not significantly modified, high efficiencies should be attainable in line with the values currently assumed in the cycle calculations.

Combustor

The input and output streams to the combustor (R1) with their compositions are given in Figure 6. The numerical investigations began from general concepts acquired in previous experience [1] and some specific design concepts were then defined for the combustor of the SCOC-CC cycle, briefly explained below. In this cycle, natural gas (S4) is burnt with an oxygen-rich stream (S5) in the combustion chamber (R1). The temperature is controlled by a recycled exhaust stream (S3). The combustor exit stream (S6) is a mixture of CO2 and steam.

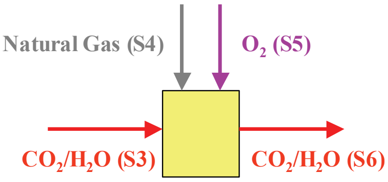


Fig. 6 – Input and output streams to combustor

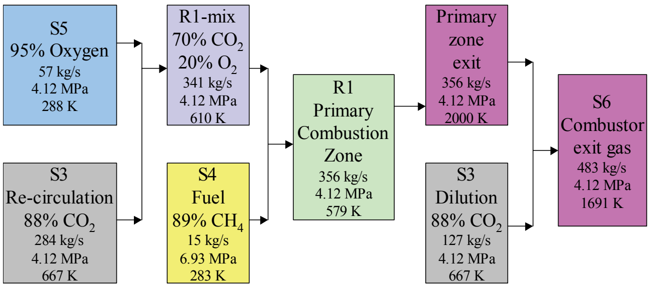


Fig. 7 – Proposed flow split for the combustor

The O_2 (S5) and part (approximately 69%) of the re-circulating exhaust gas (S3) (after it has been used for primary zone cooling) are mixed and used to give the design combustor primary zone exit temperature of approximately 2000K. The design combustor exit temperature (1691 K) is achieved by diluting the combustor primary zone exhaust gases with the remainder (approximately 31%) of the re-circulating exhaust gas (S3). The proposed flow split for this combustor, given in Figure 7, is based on one-dimensional combustor calculations.

4. Conclusions

The evaluation of all novel cycles summarized in the sheets reproduced in Fig. 4 suggests that the following cycles incorporating gas turbines would require least effort to turn them into real power plants:

- Semi-Closed Oxy-Fuel Combustion – Gas Turbine (simple cycle)
- Semi-Closed Oxy-Fuel Combustion – Combined Cycle
- Integrated Gasification Combined Cycle – Chemical Absorption
- Integrated Gasification Combined Cycle – Chemical Absorption with Air Separation Unit

This does not mean that they are the best solutions for the problem of reducing CO_2 emissions. Within other sub-projects of ENCAP other solutions are being studied for coal and natural gas. In the remainder of the project, some refinement is to be made of the evaluation and classification of components shown here and deeper analysis will be made of further components of the cycles that are in the scope of work package WP6.2.

References

1. Mina, T. and Chen, J. X., 2005, 'Combustion system design for GAS-ZEP cycle', Fuels for the Future, Institute of Physics, Cardiff, April 14.