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Assessment of a fully integrated SARGAS process operating on coal with near zero emissions

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This paper presents a novel advanced clean-coal technology, *Sargas*[1], that facilitates capture and storage of carbon dioxide (CCS) in an innovative manner. The technology combines the Alstom P200 PFBC power cycle[2] and pressurised post-combustion acid gas cleaning, with a high degree of process integration. The purpose of the paper is to convey the conceptual idea and working principle of the *Sargas* technology, and to provide reference data for further assessment studies to be performed under the EU-based EMINENT project[3]. For this survey process simulation data have been made available by Sargas AS for a coal-fired *Sargas* block rated at 100 MW_e. The modelling and calculations have been performed by Sargas and verified by a third party (Siemens) using the HYSYS Mass and Energy Balance Model.

1. Introduction

According to the *BP Statistical Review of World Energy 2006* [1] fossil fuels account for 87.7% of the global primary energy demand. This corresponds to 9.24 Gtoe per year[4], and implies that 28 Gtpa CO_2 is directly attributed to the use of fossil fuels[5]. This vast amount of CO_2 suggests that solutions including CCS have to be pursued and adapted to numerous power plants, especially those burning coal. In this setting *Sargas* responds to the UN Framework Convention on Climate Change (UNFCCC) and to the pronounced needs of most Annex-I countries for reducing their greenhouse gas emissions. According to Sargas AS, recent assessment studies suggest that the *Sargas* technology is capable of meeting a capture rate of 95% at a capture cost of around 15 Euro per tonne CO_2 reckoned at a coal-fired plant (in Norway).

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[1] *Sargas* is generally referred to as the integrated CCS concept belonging to the Norwegian-based Sargas AS, the owner of the intellectual property rights of said technology.
[2] PFBC: pressurised fluidised bed combustion, developed by ABB Carbon in the 1980'ies, and is licensed by ALSTOM Power to Babcock & Wilcox Company (USA) and IHI (Japan).
[3] Early market introduction of new energy technologies. Co-ordinated by TNO (NL). EU-contracts NNE5-2002-00075 (2002-2005) and Tren/05/FP6EN/S07.56209/019886 (2006-2009).
[4] 2005: Global total primary energy demand (PED) reached 10537.1 Mtoe whereof 9241.3 were from fossil fuels. 2004 showed 10291.0 and 9022.7 respectively, hence, a total increase in PED of 246.1 Mtoe, whereof fossil fuels accounts for 218.6 Mtoe (i.e. 88.9% of the growth).
[5] Gtpa: Gigaton per annum. The formation of CO_2 from the burning of oil is roughly 3 kg/kg oil.

2. Sargas idea

By combining the virtue of the PFBC technology with pressurised post-combustion carbon dioxide capture Sargas AS has developed an innovative clean-fossil fuel technology. The clue is a) to provide a high partial pressure of the CO_2 to allow for low-cost chemicals (e.g. carbonates) for efficient flue gas cleaning, and b) to apply a high degree of process integration to form an integral power scheme to facilitate CCS.

So far the *Sargas* capture process has been verified in a pilot gas-fired plant. The core technology is (in 2007) subjected to further testing and optimisation against a hot pressurised bleed stream from a coal-based combined heat and power plant, Värtan, in Stockholm, Sweden[6]. Although said plant has no provision for carbon dioxide capture, its power cycle is essentially the same as that of *Sargas*. Basis is the Alstom P200 PFBC power cycle that per se has been verified in industrial operations in Europe, the US, and Japan for more than 15 years [2,3].

What is new is basically the way that *Sargas* is combining current needs with prior knowledge and proven technologies in forming a complete CCS scheme, protected by intellectual rights. Jointly with early customers the owners of the *Sargas* technology have gained sufficient confidence in the technology to having signed a letter of intent (2006) aimed at an EPC contract for a 4x100 MW_e coal-based CCS plant at an aluminium smelter at Husnes in Southern Norway[7]. If realised, this plant will become the first of its kind anywhere in the world. Provided that take-offs for the CO_2 could be organised in due time - this plant could be urged to go on stream by 2011– depending, however, on site permits and other concessionary approvals.

3. Sargas concept

The *Sargas* concept is a closed loop made up in unit blocks rated at 100 MW_e. Each block includes:

1. one heavy-duty gas turbine engine characterised by external combustion,
2. one PFBC unit with integrated steam generation,
3. one steam turbine with five extractions and one cross-over,
4. a capture unit using the Benfield carbonate process.

As partly depicted in Figure 1 the high-pressure compressor diverts compressed air to the external fluidised-bed combustor (PFBC) at 300°C and 1.2 MPa. The PFBC generates superheated live steam for the steam cycle, and diverts a hot flue gas stream to the capture unit. From the capture unit the cleaned pressurised gas is further directed to the power turbine. This arrangement results in a combined cycle that offers an electric efficiency that is higher than just a steam cycle [3]. Steam properties of the *Sargas* power cycle are 565°C/16.5 MPa at inlet, the expansion line ending at 0.002 MPa and 17.9°C with 88.6% steam quality. This requires a rather low cooling-water temperature.

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[6] Since 1991 the Värtan plant produces 135 MW electric power and 220 MW heat for Stockholm Energi. It is coined the first coal-fired PFBC plant in the world.

[7] According to Sargas AS information: Consortium: SørAl AS (Alcan and Hydro Aluminium), Eramet Norway, and Tinfos. Planned investment: NOK 4500 million. Annual output: ~3 TWh and 2.5 Mtpa CO_2 (@95% capture). Decision to build: Spring 2008. Start-up: 2011.

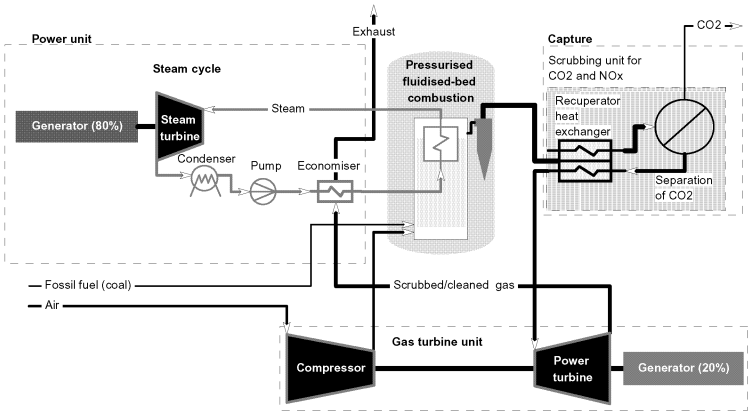

Figure 1: Simplified outline of the Sargas technology with pressurised fluidised-bed combustion technology (PFBC licenced by Alstom to Babcock & Wilcox) interlinked with the CO_2 capture process and the power turbine via a recuperating heat exchanger. The purpose of recuperation is twofold: to lower the temperature in front of the CO_2 separator unit (refer Figure 2*), and then to raise the temperature of the cleaned gas in front of the power turbine. Owing to the high system pressure the compressor is made in two sections separated by an intercooler (not shown) [4,5].*

Demonstration units based on the Alstom P200 PFBC module have been built in Europe, the U.S. and Japan. [6,7,8]. In 2001 a larger version rated at 360 MW_e using supercritical steam was delivered by IHI on the basis of the Alstom P800 module licensed by Alstom - known as the Karita project in Japan [9].
Key of the *Sargas* concept is the diversion of the hot flue gas from the PFBC combustor to the power turbine, which is routed through the low-temperature capture unit. Thereby the flue gas has to pass twice through the recuperating heat exchanger: Once to drop the temperature (from 854 to 350^oC), and then - after CO_2 removal - to recover the temperature level (from 234 to 814^oC) until entering the power turbine (Figure 1). Verification and design optimisation of the recuperating process of *Sargas* will take place during early 2007.

3.1 Gas turbine

The current *Sargas* technology builds on the Alstom GT35P gas turbine rated at 14-17 MW_e depending on the coal[8]. The GT35P machine was designed in the late 1980-ies for operations with flue gas from various coals, which implies that it is specially made to withstand erosion, fouling and corrosion. It is regarded as a turbocharged, constant speed gas turbine [2,3]. The reliability is high with a down-time of just about 2% [10].

3.2 Pressurised fluidised-bed combustion

The *Sargas* cycle involves combustion of the solid fuel in the PFBC unit, in which live steam for the steam cycle is generated in boiler tubes immersed in the fluidised bed. The combustion pressure is around 1.2 MPa [2]. Hence, the fluidisation of the PFBC bed

[8] Pressure ratio 13. Flue gas inlet temperature outlined at 850^oC. Number of stages: LPC: 11, HPC: 12, HPT: 4, LPT: 1.

material requires compressed air supplied by the high-pressure compressor of the gas turbine. Usually the fuel is introduced as a coal-water slurry. Particles from the fluidised bed combustion will be trapped by cyclones (up to 98%). The remaining part is removed in the capture unit.

Inherently, the PFBC technology is associated with very low emissions of air pollutants. Owing to the low bed temperature, typically around 850 to 880°C, the formation of nitrogen oxides will be very low (thermal NOx < 5 ppm). Further sulphur capture may be obtained by adding some dolomite or other additives. Sulphur capture may even improve as the temperature goes beyond 850-880°C, although a high bed temperature may increase other risks such as bed agglomeration - depending, though, on the fuel [3].

3.3 Power cycle

It is known that in conventional natural-gas-combined-cycle power generation (NGCC) the electricity generated by the gas turbine versus the steam turbine is roughly 80/20. In contrast, the duty sharing of the *Sargas* concept is almost the opposite, as less than 20% of the net power output owes to the gas turbine and the remaining part to the steam cycle. The low yield of the gas turbine is claimed to offer an advantage over other clean coal technologies (IGCC) in terms of versatility, availability and turbine life. The gas turbine of the *Sargas* cycle operates at a fairly low turbine inlet temperature (TIT 814^{o}C), which implies a significant turbine life in comparison with the highly loaded top cycles in advanced gas turbines with a TIT around 1300^{o}C. Furthermore, the *Sargas* power plant offers large quantities of low-grade heat that is readily available for district heating, thus envisaging a total energy utilisation index of around 90%.

3.4 Capture unit

The *Sargas* CO_2 capture process employs the Benfield carbonate capture process[9], which is a thermally regenerated cyclical solvent process that uses an activated, inhibited hot potassium carbonate solution for removing the CO_2 [11]. The removal efficiency is as high as 98% for CO_2 capture compared with 85% for MEA in combined cycles, and potassium carbonate is less sensitive to degradation than amines [10].

The Benfield process is deemed a simple, stable and oxygen tolerant capture process that has been used in the industry for around 40 years – especially in treating synthesis gas in ammonia plants. It is also used to pre-treat natural gas to achieve either LNG or pipeline specifications. The key driving force for this process is the partial pressure of the CO_2. According to UOP information [11], typical feed conditions may range from 1-12.5 MPa with acid gas concentration ranging from 5% to more than 35% by volume. In the study case of *Sargas* the CO_2 concentration amounts to 16.4%. The high partial pressure is prone to reduce the heat demand for regeneration [10]. Typical heat consumption is 70-90 MJ/kg,mole of CO_2 removed (30-40 kBtu/lbmole). This corresponds to 0.44-0.57 kWh per kg CO_2 captured, usually supplied as low-grade steam extracted from the low-pressure steam turbine. In order to keep pace with the rate of processing demands, the Benfield process operates at a relatively high temperature (90^{o}C plus).

[9] Supplied by the US-based UOP LLC

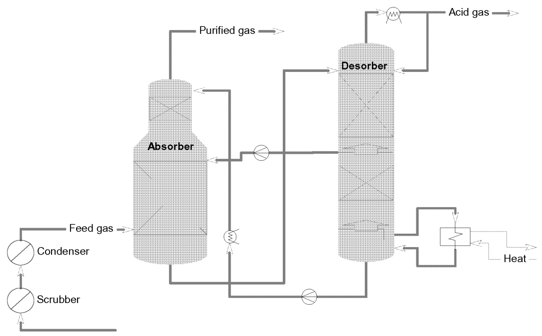

Figure 2: The Benfield carbonate capture process using carbonates for CO_2 absorption.

Furthermore, the *Sargas* capture process is not necessarily linked with carbonates. Other absorber types with different characteristics may apply as well, as indicated in Table 1.

Table 1: Cleaning alternatives for flue gas under pressure (Dons, 2007 [5])

Absorber type	*Characteristic of absorber*
Amines	More efficient than other absorbents at atmospheric pressure (Fluor Econamine, MHI KS-1). Challenge: Control of corrosion and amine degradation. Limited references for this application, at least two major amine vendors remain apprehensive.
Carbonates	Stable, simple process. Oxygen tolerant without solution degradation. Many relevant references, 90 to 99% CO_2 absorption possible with standard plant design. Requires pressurized system (10 bara+, partial pressure CO_2 0.5 bara+)
Amino acids	Old and well-known process. Oxygen tolerant, biodegradable. Possibly a future candidate for *Sargas*
Physical absorption	Difficult to achieve 90% CO_2 absorption.

4. Sargas technology metrix

The following table summarises some main characteristics of the *Sargas* technology in plain numbers that may form input to technology assessment by the EMINENT project.

Table 2: Current Sargas plant metrix:

Feature (100 MW unit block)	*Value*	*Comments:*
Overall plant efficiency (HHV) - %	39.30	Not accounting for CO_2 compression
Fuel supply kg/s	7.5	Dry coal. HHV equals 33.927 MJ/kg
Unit power - MW_e	100	Full plant 400 MW_e requiring 4 unit blocks
CO_2 generated – kg/s	26.47	
CO_2 captured – kg/s	23.92	Thus emitting 2.5518 kg/s CO_2
CO_2 capture rate - %	90.36	
Investment – Million USD	215.	Coal-based plant Norway
Power output per annum - GWh	750	Reckoned at 7500 hours operation per year
CO_2 for storage – ktpa*	715	400 MW plant: 2.86 Mtpa CO_2
CO_2 emission - ktpa	70	400 MW plant: 280 ktpa CO_2
Fuel Cost assumptions – USD/tonne	65	EC 2006 (Dons, 2007, [5])
Cost of Electricity - USD/MWh	6	Mature 400MW 20-25% lower COE

- Investment, OPEX etc. - USD/MWh	*4*	
- Fuel element – USD/MWh	*2*	
Technology maturity level (TML)**	4	Ready to bid 2007

*ktpa denotes kilo-tonne per annum (or 1000 tonne per year). Mtpa is mega tonne per annum.
**According to EMINENT denotion: TML-1: Paper idea, TML-2: Laboratory tests performed, TML-3: Pilot testing performed, TML-4: Demonstrator tests performed, TML-5: Commercial stage.

Conclusion:

Sargas constitutes a new promising energy technology aimed at power generation from fossil fuels – especially coal, as it employs a complete CCS scheme characterised by pressurised post-combustion capture. *Sargas* is deemed capable of obtaining a capture rate that exceeds 90%. Its conversion efficiency is close at 40% (HHV) based on a 100 MW_e unit block. Furthermore, *Sargas* makes use of compact equipment of proven design that offers low extra investment cost in CO_2 capture, and the penalty for pressure losses becomes rather low [10]. However, despite the somewhat higher fuel penalty, the present *Sargas* cycle offers cost-advantages over other comparable capture concepts, and it is stated as being reliable.
Demonstrations tests are being performed in early 2007 aimed at verification and optimisation of core elements of the technology. On this basis it is supposed that the *Sargas* technology will be deemed commercially available within 2007.

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