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*Front cover: Ramgen 8 MW, 10:1 pressure ratio CO2 compressor being assembled for test on the Dresser-Rand dedicated closed-loop CO2 test facility in Olean, NY, USA*

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# Contents

# Alstom and Dow progress on amines

Since the creation of the Joint Development Agreement between The Dow Chemical Company and Alstom in 2008, both companies have investigated improvements to the Advanced Amines Process technology (AAP) through innovative changes to the conventional amines process flow scheme. Recent developments with the AAP technology in absorption and regeneration methods will be demonstrated at a facility in EDF's coal-fired power plant in Le Havre, France.

**By By Larry Czarnecki and Davy Theophile (Alstom Power), Fabrice Chopin (Électricité de France), Craig Schubert and Eric Klinker (Dow Chemical Company)**

A variety of $CO_2$ capture technologies are currently being developed. Many of these development programs rely on collaboration between utility companies, universities and government agencies. A promising post-combustion solution is the AAP, jointly developed by Alstom and the Dow Chemical Company (Dow). The AAP relies on an advanced amine solvent, UCARSOL™ FGC 3000, developed by Dow specifically for $CO_2$ capture from combustion gas.

The AAP technology is validated and implemented in various steps: First a small size pilot plant, capable of capturing 5 tonnes $CO_2$ per day and located in South Charleston, West Virginia USA was set up. Following this demonstration facility a partnership between Électricité de France (EdF) and Alstom was established. The Charleston pilot plant at Dow's facility was used to develop the data and operations experience necessary for the design of larger, subsequent plants and to investigate the impact of equipment features and process operation on overall system performance. It also provided the platform for the development of suitable amine management strategies.

*Figure 1 - The AAP pilot plant facility in Charleston, West Virginia, U.S. is capable of capturing 5 tonnes of CO2 per day*

The EdF Le Havre demonstration unit features the latest Advanced Amine Process design for the absorber, regenerator and thermal management systems and will reduce energy consumption and minimize solvent degradation. The mentioned process will be fully studied for process performance, operational flexibility and emissions. EdF's Le Havre new demonstration facility has been granted of a partial funding from ADEME (the French Environment and Energy Management Agency).

Pilot plant, demonstration unit operational results and model development efforts will be used to improve the predicted performance of larger demonstration plants (around 250 MWe) that are currently under development in Europe as part of the EU Flagship programme.

## AAP technology: process and solvent

The AAP technology is based on the chemistry of the amine-$CO_2$-$H_2O$ system and the ability of amine solution to absorb $CO_2$ at low temperatures and release it at moderately elevated temperatures. $CO_2$ reacts with aqueous amines in an absorption column, forming chemical compounds, resulting in the removal of $CO_2$ from the gaseous stream. In the proposed process $CO_2$ is absorbed in the amine solution at a temperature of around 40°C and at atmospheric pressure.

Flue gas from the boiler is picked up downstream of any installed Air Quality Control System (AQCS). Concentrations of $NO_2$, $SO_2$, $SO_3$, HCl and particulate matter need to be kept relatively low to prevent co-absorption, amine solution degradation as well as equipment fouling. Additional AQCS equipment may be needed to meet these requirements.

A booster fan is used to drive the flue gas through the $CO_2$ absorber in which the $CO_2$ reacts with the lean amine solution. The treated gas exits at the top of the absorber tower. Typical target $CO_2$ removal efficiency from the flue gas is 90 %, although a suitably designed absorber can operate at removal efficiencies ranging from 50 % to 99 %.

The system consists of two main blocks, the $CO_2$ absorber, where the $CO_2$ is absorbed into an amine solution via fast chemical reaction and the regenerator system, in which the amine is regenerated and then sent back to the absorber for further absorption. The AAP relies on regeneration performance to reduce the operating cost of $CO_2$ capture from combustion gas.

The regeneration operation reduces the re-boiler duty necessary to regenerate UCARSOL™ FGC3000 and produces $CO_2$ suitable for compression and pipeline transportation. The rich amine exiting the $CO_2$ absorber is sent to the top of the regenerator section via a cross heat exchanger. Desorption of $CO_2$ occurs within a regenerator that includes heat integration features. Thus, the energy content in the flashed water vapour partially recovered as $CO_2$ is released from the rich solvent. The heat integration features also allow control of both temperature and amine solvent flow rate in the lower part of the absorber column.

The $CO_2$ absorber is designed as a packed tower. The absorber is filled with a packing material, layered in several beds to maximise $CO_2$ absorption. The height of the packing is determined by the desired $CO_2$ removal efficiency and the amine circulation rate. The diameter of the absorber is based on the flue gas flow with the aim of maintaining a constant column loading factor.

The absorber includes an inlet duct designed to evenly distribute the gas in the packed bed. Lean solution returning from the bottom of the regeneration column is cooled to the operating temperature at the top of the absorber in the lean cooler by heat exchange with cooling water or air.

The regeneration column may contain trays or packing. Rich solution flows down the regeneration column counter-current to rising steam produced by boiling part of the lean solution exiting the bottom of the column. Gaseous $CO_2$ and water vapour exit the top of the regenerator where residual water is condensed. The condensed water is then sent to the top of the regenerator or to the make-up water system.

*Figure 2 - the EdF Le Havre demonstration unit features the latest Advanced Amine Process design for the absorber, regenerator and thermal management systems and will reduce energy consumption and minimize solvent degradation.*

## Charleston pilot plant

The Charleston pilot plant, jointly operated by Alstom and Dow since September 2009, treated a flue gas slip stream from a bituminous coal-fired process boiler and achieving 90 % $CO_2$ capture efficiencies using UCARSOL™ FGC3000 series of solvents.

The main objective of this pilot was to gain both amine solvent management and process system operating experience on coal-fired flue gas for an extended duration. As the design of the Charleston pilot plant offered a wide range of process configurations, various improved flow schemes were examined in comparison to a conventional, basic flow scheme. Process performance parameters such as $CO_2$ capture efficiency, amine solvent and flue gas flow rates, and thermal duties of different flow schemes were examined in parallel.

The long-term impact of oxygen and trace contaminants present in the flue gas on the stability of the solvent were studied by examining several issues:

- Impact of exhaust gas trace pollutants on AAP performance (efficiencies/duties)
- Impact of accumulation of oxidative and thermal degradation products on process performance (efficiencies/duties)
- Amine make-up rates needed to maintain $CO_2$ removal efficiency
- Amine reclamation to maintain heat stable salts and other degradation products at acceptable levels
- Emission of amines and associated amine degradation products
- Analytical methods suitable for monitoring the amine solvent composition

The information obtained from the Charleston pilot plant has been used to determine further process improvements for minimal energy consumption levels and to validate the simulation tool used to engineer the pilot plant facility.

In addition, the solvent management principles have also been demonstrated, including solvent integrity and overall system performance maintenance. Strategies for amine solvent and heat stable salt management have also been demonstrated.

## EdF Le Havre demonstration facility

The demonstration unit at Le Havre, France, has been designed to capture 25 tonne $CO_2$/day from the flue gas exiting boiler No. 4 at a 600 MWe hard coal-fired plant owned by EdF. The boiler is equipped with a selective catalytic reduction (SCR) system for NOx control, an electrostatic precipitator (ESP) for controlling particulate emissions and a limestone wet flue gas desulphurisation (WFGD) for SOx control.

A nominal 5000 Nm3/hr slipstream of exhaust gas (nominally 2 MWe) is withdrawn from the WFGD exhaust stack and directed to the demonstration unit. The scrubbed flue gas stream and the CO2 product stream are both returned to the main exhaust duct leading to the plant chimney. Process steam is provided from the boiler steam supply and demineralised water is provided from the plant utilities. The major process configuration consists of a two-section absorber column, a single section regeneration column and associated heat management equipment.

The exhaust gas from the WFGD is routed through a sodium-based desulphurisation unit that reduces the SOx content to below 20 ppm prior to introduction to the absorber column. A blower provides the pressure necessary to drive the gas through the CO2 absorber. The absorber is equipped with a water wash section to minimise amine vaporisation losses during CO2 capture operations. The absorber is designed to remove 90 % of the incoming CO2 from the inlet flue gas stream. The absorber column contains structured packing selected for optimal CO2 capture (mass transfer) and pressure drop (hydraulic) characteristics.

The demonstration unit regeneration column contains random packing and is thermally driven by a steam re-boiler unit equipped with a steam de-superheater. The exiting CO2 gas product stream is cooled and dried in a cooling section located in the regeneration column. The CO2 product pressure is relieved prior to discharge to the plant exhaust duct.

All columns along with the amine circuit use stainless steel materials to allow future operation on other amine solvents. The amine circuit features rich-lean solvent cross heat exchangers and lean solvent coolers for optimal process conditions. All cooling units are air-cooled to minimise process water consumption and associated piping.

Amine solvent management is accomplished with the use of mechanical filters, an activated carbon bed filter and an Electro-Dialysis (ED) reclamation unit. The ED reclamation unit converts heat stable amine salts, formed from trace acid gas products in the flue gas, into usable amines while eliminating the undesired acid anions. The ED reclamation unit also selectively removes some undesired amine degradation products. The ED reclamation unit employs ion selective membranes in an electric field to segregate and extract the unwanted anions from the amine solvent stream. Caustic is used during the reclamation process to neutralise the heat stable amine salts during the membrane filtration.

The amine circuit also has an oxygen scrubber to minimise amine oxidative degradation caused by oxygen absorbed from the flue gas. The oxygen scrubber treats the rich amine solvent exiting the CO2 absorber, where the solvent is exposed to a reduced pressure environment to promote the desorption of oxygen gas. The oxygen scrubber is designed to extract absorbed oxygen from the amine solvent stream with minimal impacts on solvent composition or affecting the CO2 load of the solvent. Flue gas condensate and reclaimed wastes are collected local to the demonstration unit for characterisation prior to further disposal.

The demonstration unit control system is instrumented to observe and record process performance and unit operation details. The control system is fully automated to support continuous operation of the plant. Gas stream CO2 and pollutant compositions system are continuously monitored using NDIR flue gas analysers with several access locations provided for gas sampling and testing.

## Test program objectives

An on-site laboratory will be set-up to support the demonstration unit operations. This laboratory will be equipped with several analytical instruments for evaluating amine solvent characteristics and process operation performance.

One key aspect of an amine-based CO2 capture facility being the emission of amine solvent and the associated degradation products in the exiting flue gas stream, (this is a concern as an environmental issue and an operating cost), the test programme at EdF Le Havre facility will continue to assess the emission levels for the latest AAP flow scheme. Moreover, the demonstration unit featuring the minimising of the oxidative degradation by scrubbing absorbed oxygen from the amine solvent, the impact of this treatment on emissions and overall demonstration unit performance will be investigated at the facility. In addition, due to Le Havre Power Plant operation profiles, the impact of the transient operation will be particularly tested at Le Havre facility.

The first year of operation will focus on executing a test programme to meet Alstom's and EdF's mutual objectives. The proposed programme will address the following issues:

1. Verification of key process-related objectives such as: CO2 capture efficiency, thermal performance and solvent management of the AAP technology.

2. Validation of AAP flow scheme including process tuning and stability mapping.

3. Comparative environmental study of advanced amine solvent UCARSOL™ FGC 3000, including gaseous emissions along with any liquid and solid waste streams.

4. Study of the impact of oxygen stripping on the degradation of amine solvent by correlating oxygen content against changes in solvent composition and AAP system performance.

5. Study of the performance of amine reclamation by electro-dialysis during operation for efficiency and waste stream characterisation.

6. Assess the corrosion resistance of steel and non-metallic materials at key locations in the demonstration unit.

7. Demonstrate AAP technology robustness and behaviour during transient operating modes such as load variations and "cold" and "hot" start-ups and shutdowns.

It is expected that some of the test objectives will be studied continually throughout the entire test programme, while others will be studied either intermittently or sequentially. The operation of the first pilot plant in Charleston has demonstrated the basic operation and solvent maintenance strategies of the AAP process when treating flue gas from a coal-fired boiler.

## Conclusion

Alstom and Dow have been actively involved in the development of the Advanced Amine process since 2008. The advancements and opportunities learned from the Charleston facility have been applied to the design of the AAP demonstration unit installed at EdF Le Havre and define the test program needed to complete the AAP validation program.

With defined test program, this facility will demonstrate and detail the performance characteristics of the latest AAP process flow scheme for energy efficiency, emissions and amine solvent management methods.

The operating practices and process performance findings from these both facilities will support on capitalizing for large scale demonstration plant (around 250 MWe) to finally validate the performance of the most promising advanced flow scheme and corresponding optimized process conditions. Alstom is currently designing its first large-scale Advanced Amine Process demonstration plant for PGE Elektrownia Belchatow S.A. in Poland with an estimated start-up in 2015.

## More information

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# CO2 Capture in vehicles and home heating

Strataclear® is the first CO2 capture technology for moving vehicles and home heating systems. It is an innovative carbon capture technology that removes CO2 from exhaust gasses up to: 25% in automobiles; 40% in trucks; and, 50% in home heating furnaces. Moreover, the technology produces a clean solid residual material that can be sold for use in many industrial applications.

**By Donald G. Rynne, Ryncosmos LLC**

The Strataclear system is a unique emission reduction technology that will enable the capture and disposal of carbon dioxide gas from moving vehicles and home heating systems.

A specially designed system, Strataclear includes removable absorber cartridges that replace the resonator and muffler in a vehicle's exhaust system. The solid absorber never changes its form even when it is completely spent. Nor does it impede the flow of the exhaust or engine performance. Contained in a CO2 capture device, the absorber cartridges are simply stored along the perimeter of the car trunk until they are easily replaced at a gas station or another exchange facility.

With patent pending from New York-based Ryncosmos, LLC, the new technology reduces carbon emissions from any type of internal combustion engine. The exhaust gases pass the catalytic converter then enter the Strataclear® exhaust treatment system where CO2 is absorbed. The purified exhaust with reduced CO2 is emitted from the tailpipe where it captures up to 25% of carbon dioxide in automobiles and 40% in trucks.

In home heating systems, the technology captures as much as 50% carbon dioxide, providing the user with a 37% savings on gas or oil heating bills. The by product is a clean chemically inert material captured in the absorber that can be safely stored and used broadly in numerous exciting industrial applications, creating great potential for viable profit centres.

Following extensive tests at its Program for Advanced Vehicle Evaluation (PAVE) facility, Auburn University certified the Strataclear technology. The testing was done with a small diesel car equipped with the emission reduction technology. The car made intensive round trips on the Auburn test track at different speeds over a two-day period. The collected data were analysed by University researchers who certified to the efficacy of the carbon dioxide emissions. They also certified they found no adverse effects on engine efficiency. As a result of this testing, Ryncosmos and Auburn University instituted a close academic working relationship.

*Figure 1 - a prototype of the Strataclear technology installation in the trunk of the test vehicle. Pipes and cables in the car trunk are only for testing purposes, performed using the computerized industry standard, five gas analyzers, complemented with On Board Diagnostics version II reading of the engine data. This is typically performed by the car servicing station, to diagnose problems and collect data. The analyzers and part of the exhaust gas conduits are visible in the trunk.*

Although great strides have been made to reduce CO2 emissions, its storage and disposal is an ongoing issue. Most CO2 capture technologies produce liquid form residue, which must be carefully disposed of deep underground or under the ocean floor. Strataclear®'s residue is a clean solid dynamic material. The technology changes the traditional way we view Carbon Capture and Storage (CCS), which for many evokes a large scale installation similar in size to a power station or plant full of complex equipment such as valves, pumps and exchangers.

The Strataclear residual material has economical and product-enhancing potentials that touch many industries. Among them are construction, road building, iron smelting and pulp and paper. It can also be used for sulphur removal from flue gases and in glass making, sewage treatment plants and coal mining.

Preliminary results from in-house testing of the technology's residual with sheetrock and bricks concluded the following:

1) Sheetrock becomes much lighter when 50% of the gypsum is replaced with the residual. Moreover, when it is subjected to 1000° F for six minutes there is no penetration. The standard sheetrock, on the other hand - made with 100% gypsum and subjected to the same heat for half the time - showed penetration.

2) A standard brick consisting of equal parts cement and sand weighs a third more than a brick with equal parts cement and the residual material. Not only is the cement/residual brick much stronger but it

*Figure 2 - small diesel car equipped with the emission reduction technology making intensive trips on the Auburn University test track at different speeds to test carbon dioxide emissions and the technology's effect on engine performance. Auburn certified to both the efficacy of the CO2 emissions that there were no adverse effects on engine efficiency*

appears more resistant to heat and cold.

Further research and scientific testing is currently underway at the Auburn University PAVE facility to evaluate and certify the residual's many applications in numerous industries. Nonetheless, the in-house testing conducted so far has shown exciting results making its potential for sustainable profit centers very real.

## The policy of CO2 reduction in vehicles

In late March 2012, AutoNews Europe reported that by 2015, the auto industry must reduce CO2 emissions from new cars sold in Europe to a fleet average of 130 grams per kilometer. Last year's average was 140.9g/km, down from 145.9g/km in 2009, according to an analysis of 21 European markets by JATO, an automotive intelligence provider.

The magazine went on to cite Toyota Motor Corp., PSA/Peugeot-Citroen SA and BMW AG as the automakers closest to reaching their EU-mandated CO2 targets. Toyota, PSA and BMW need to cut their overall fleet emissions by 7 percent or less to comply with the tougher emissions regulations, which start to take effect next year.

Daimler AG, Mazda Motor Corp., and Nissan Motor Co., will need to speed up the pace of their CO2 cuts to help the industry reach its overall goal. If the automakers fall short, they will face steep fines, which have been established from 2012 to 2018. Most industry experts say it is unlikely automakers will miss their targets.

As new engine technologies shift toward cheaper, smaller, lighter vehicles, said JATO, this will help automakers' CO2 emissions. For example, Toyota only needs to cut its fleet CO2 by 4.2 percent by 2015 to reach its EU target of 20% reductions by 2020. Overall, Toyota ranked second in Europe last year based on average CO2 emissions of 130.0g/km while Fiat had the lowest CO2 emissions at 125.9g/km. They need to drop down to 116.1g/km – an 8.4 percent decrease – by 2015, according to JATO's “A Review of CO2 Car Emissions Across Europe FY 2010” report.

The new carbon capture technology clearly complements efforts to build smaller cars with more efficient engines at a fraction of the cost.

In 2008, carmakers lobbied aggressively to extend by three years a deadline for average new car CO2 emissions to reach 130g/km. As a result, the EU postponed the target year from 2012 until 2015.

Industry experts say the next goal of 95/g/km by 2020, is going to be hard to achieve pointing to the next step and beyond becoming, “…. ever more challenging and expensive” as they focus on the “need to make [auto] parts out of magnesium and other exotic expensive materials,” says AutoNews.

To reduce the amount of CO2, a gas blamed for climate change, the EU set automakers' individual CO2 reduction targets as part of a goal to cut average new-car emissions in Europe overall to 130g/km by 2015 from 160g/km in 2006. The 130g/km figure is equivalent to fuel consumption of about 5.6 liters of gasoline or 4.9 liters of diesel fuel per 100 km.

Pressed by French and German automakers, the EU also introduced a weight-based system that sets individual targets for each automaker. Fiat, which sells mainly small cars, had the lightest average weight for its models at 1,067kg last year compared with 1,337kg in 2009.

## CO2 emissions control in the U.S.

Worldwatch, an independent research institute devoted to global environmental concerns, reported a year ago the California legislature passed a bill establishing the most extensive CO2 emission controls in the United States.

The law requires a 25 percent reduction in state CO2 emissions by 2020, with the first major controls taking effect in 2012. The California Air Resources Board, the agency that enforces the state's air pollution controls, will be the main authority in establishing emission targets and noncompliance penalties, which also allows for business incentives to reach the goals.

The research institute also reported several northeastern U.S. states signed a regional agreement to reduce CO2 emissions back in December of 2005 but their target would reduce emissions by only some 24 million tons. The California mandate, which aims to cut emissions to their 1990 level, will result in cuts of some 174 million tons.

Supporters hope the legislation will instead inspire other states -- and eventually the federal government -- to follow suit said Worldwatch.

President Obama has repeatedly reiterated his support for an aggressive effort to reduce U.S. emissions of greenhouse gases, according to the National Centre for Public Policy Research. He promised to reduce U.S. emissions to 1990 levels by 2020 - a cut of about 16 percent - and then to cut them an additional 80 percent by 2050. That's an overall cut of 68 percent from today and would mean trimming U.S. carbon emissions to roughly where they were in 1905.

Note: All emission estimates from the Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2010.

According to the EPA (Environmental Protection Agency), the main human activity that emits CO2 is the combustion of fossil fuels (coal, natural gas, and oil) for energy and transportation, although certain industrial processes and land-use changes also emit CO2. The EPA cites Electricity, Transportation and Industry as the main sources of CO2 emissions in the United States.

Electricity: Coal burning to produce electricity generates more CO2 than oil or natural gas accounting for 40% of total U.S. CO2 emissions and 33% of total U.S. greenhouse gas emissions in 2009.

Transportation: The combustion of fossil fuels such as gasoline and diesel to transport people and goods is the second largest source of CO2 emissions, accounting for about 31% of total U.S. CO2 emissions and 26% of total U.S. greenhouse gas emissions in 2010. This category includes transportation sources such as highway vehicles, air travel, marine transportation, and rail.

Industry: Many industrial processes emit CO2 through fossil fuel combustion. Several processes also produce CO2 emissions through chemical reactions that do not involve combustion, for example, the production and consumption of mineral products such as cement, the production of metals such as iron and steel, and the production of chemicals.

Various industrial processes accounted for about 14% of total U.S. CO2 emissions and 20% of total U.S. greenhouse gas emissions in 2010. Note that many industrial processes also use electricity and therefore indirectly cause the emissions from the electricity production.

Given one kg equals approximately 2.2 pounds, one US gallon of fuel when completely burned, on average produces CO2 emissions, as follows: Diesel: 9.96 kg or 5,070 liters in normal pressure and temperature; Biofuel: 9.42 kg or 4,800 liters; and, Gasoline: 8.71 kg or 4,400 liters resulting in 22, 21 and 19 pounds of CO2, respectively, while furnaces emit 50% more carbon dioxide. A reduction of 25% CO2 emissions or more moves an entire fleet of trucks into compliance.

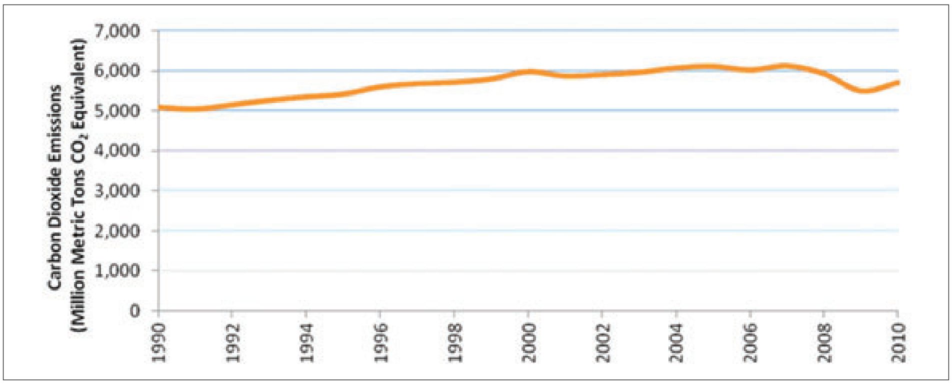


*Figure 3 - US CO2 Emissions: 20-year graph from 1990-2010 (Source: Worldwatch)*

## A new way to control emissions

Car and truck manufacturers, who must comply with impending legislation, including the US existing and proposed CAFE (Corporate Average Fuel Economy) standards, US regional and state standards as well as more strict regulations in Europe and other countries, will find an effective solution in the new technology. As such, Ryncosmos sees the establishment of a new industry, which creates thousands of jobs and generates large profits.

Most countries regulate emissions from moving vehicles in some fashion including both the air quality emissions (carbon oxide, nitrogen oxides, hydrocarbons etc.) and GHG (greenhouse gases), chiefly CO2. The regulation sets targets either directly on the CO2 emissions or on fuel consumption.

Moreover, the majority of European countries, Japan and the US set such standards and/or market-based programs. In California a bill was passed launching the most extensive CO2 emission controls yet in the United States. The law calls for a 25 percent reduction in state CO2 emissions by 2020. It takes effect this year. On the East Coast all states except New Jersey have embraced the Regional Greenhouse Gas Initiative.

In the US, the EPA standards are estimated to achieve a fleet-wide level of 155 g/km of CO2 in model year 2016 and its proposed standards are estimated to achieve a fleet-wide level of 101 g/km of CO2 in model year 2025 (passenger car target is 89 g/km CO2, the light truck target is 126 g/km CO2).

Strataclear's dual application is the answer to reducing CO2 emissions and capturing carbon efficiently and safely. Due to its great economic potential, it can reduce the cost to manufacture a car, lower home heating costs substantially, and all the while it can provide a profit center by recycling its byproduct, which has wide applications across industry. It's a win-win and most importantly it "greens" the world and brings us the future today.

### More information

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# The Past, Present and Future of CO2 Compression

Dresser-Rand has a rich history in carbon dioxide (CO2) compression, yet there is always room for improvement. This is why Dresser-Rand joined forces with Ramgen Power Systems LLC in 2008 to develop solutions that address the future of CO2 compression.

**By Mark Kuzdzal, Director, Business Development, Dresser-Rand and Pete Baldwin, President, Ramgen Power Systems LLC**

Dresser-Rand has supplied reciprocating and centrifugal compressors for CO2 compression for more than 80 years. The first unit, a reciprocating compressor, went into service in 1928, and the company shipped its first centrifugal compressor for CO2 service in 1948.

Dresser-Rand has shipped more than 400 reciprocating and centrifugal CO2 compressors totaling more than 900,000 BHP (671 MW) and believes it has the largest installed base of CO2 compression equipment in the world. More than 250 of these units are on CO2 injection service, totaling more than 500,000 BHP (372 MW).

The highest pressure achieved using a CO2 centrifugal compressor is more than 8,000 psia (550 bar), while the maximum inlet flow is greater than 48,000 acfm (82,000 m3/hr.). With a CO2 reciprocating compressor, the maximum discharge pressure achieved is more than 6,000 psig (425 bar) and the maximum inlet flow exceeds 4,000 acfm (7,000 m3/hr.).

*Figure 1 - Ramgen 8 MW, 10:1 pressure ratio CO2 compressor being assembled for test on the Dresser-Rand dedicated closed-loop CO2 test facility in Olean, NY, USA*

The reinjection process is an enhanced oil recovery (EOR) technique that helps bring more oil to the surface by both pressurizing the well and reducing the oil's viscosity. The first CO2 re-injection project developed specifically to mitigate greenhouse gas emissions began operation in August 1996 in the North Sea. As of 2012, more than 16 million metric tonnes of CO2 have been injected at this site (approximately 1 million metric tonnes of CO2 per year). The CO2 is captured by an amine plant and stored in a saline aquifer. The objective is to reduce the CO2 content in the methane from 9 percent to 2.5 percent, so that the methane can be exported as "sales gas". Compressor availability has been reported at 98 to 99 percent.

## Past to Present

On May 4 2012, a successful hydrocarbon test was performed on a DATUM® Frame 6 centrifugal compressor in Olean, New York, USA. This was the highest discharge pressure CO2 compressor ever tested on hydrocarbon in Olean at more than 8,250 psig (581.4 bar), with a suction pressure of approximately 3,500 psig (241 bar). Also, this compressor is believed to be the highest density compressor ever manufactured and tested in the world, 34.7 lbm/ft3 (556.2 kg/m3), compressing gas that has a molecular weight of approximately 36 and consists mainly of carbon dioxide. This unit was purchased for a floating production, storage, and off-loading (FPSO) vessel gas reinjection project for offshore Brazil.

In order to predict the CO2 compressor performance (specifically the head and power requirement), it is critical to use the correct gas properties. Although high-pressure gas properties do exist for CO2, the addition of methane to the gas at these discharge pressures does change the gas properties and can create uncertainty in aerodynamic performance predictions. As a result, extensive gas property testing was conducted with the field simulated gas mixture to ensure accurate performance predictions. Full-load, full-pressure testing results were such that, as tested, head and power aerodynamic performance curves matched the predicted curve and head and power guarantees were achieved.

Typically, as the power, gas density and discharge pressure of a centrifugal compressor increase, there is concern that rotor vibrations will increase, particularly sub synchronous vibrations. However, through its R&D activities, Dresser-Rand developed advanced bearing and sealing technologies that actually improve rotordynamic stability as power, gas density and discharge pressure increase.

This was demonstrated during a rotordynamic stability test at full-load and full-pressure using a magnetic bearing exciter to impart asynchronous forcing functions into the rotor while operating at full speed and load. The purpose of the testing is to evaluate the robustness of the design by "exciting" the compressor to extract a stability parameter known as logarithmic decrement. During testing of the 8,250 PSIA (581.4 bar) compressor, the logarithmic decrement was measured as the compressor discharge pressure was increased. Again, the testing results matched the predictions, confirming that the rotor became more stable as power, gas density and discharge pressure increased. The testing validated both mechanical and aerodynamic robustness and successfully mitigated risk prior to field operation.

## A New Era in CO2 Compression

CO2 compression is on the dawn of a new era. Dresser-Rand is working with Ramgen Power Systems LLC to develop the next generation of low-cost, high-efficiency CO2 compressors. The joint engineering team is developing a unique shockwave compression technology for use on high molecular weight gases like CO2. The primary goal is a low-cost, high-efficiency CO2 compressor that will significantly reduce the overall capital and operating costs of carbon capture, utilization and storage (CCUS).

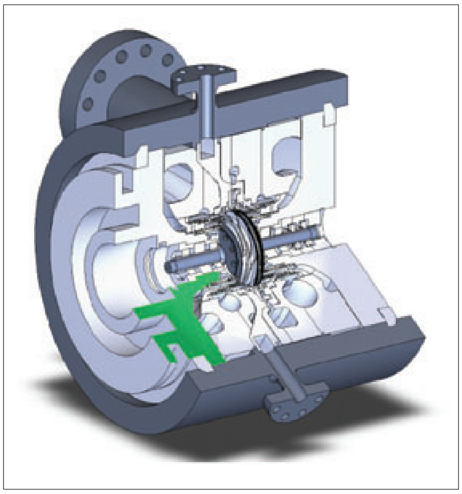

*Figure 3 - Ramgen single-stage solid model – high-pressure CO2 compression stage*

CO2 compressors represent approximately one-third of the capital and operating cost of a post-combustion, amine-based CCUS system. The CO2 compressor power required for a pulverized coal (PC) power plant is eight to 12 percent of the plant rating, depending largely on the suction pressure. A 1,000 MW PC plant would require 134,000 hp (100 MW) for CO2 compression at an estimated $150 million in equipment cost for the current 3 x 50% configuration, in addition to $75 - $100 million in installation costs.

Part of the reason that existing CO2 compressor designs are expensive is because the overall pressure ratio is anywhere between 100:1 and 200:1.The most significant impact on cost, however, is an aerodynamic design practice that limits the stage pressure ratio on heavier gases such as CO2. Conventional centrifugal compressors typically require eight to 12 stages of compression to meet the requirements of these applications. ["Low-Cost High-Efficiency CO2 Compressor," Carbon Capture Journal Sept-Oct 2009].

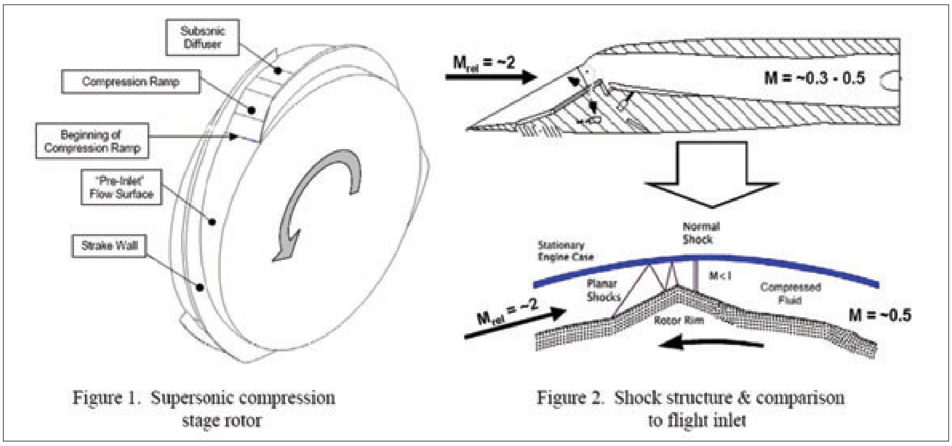


*Figure 2 - Ramgen compression technology is based upon proven, supersonic flight inlet structures.*

## Ramgen Technology – Looking Toward the Future

Ramgen's shockwave compression technology is expected to represent a significant advancement for many compressor applications, and specifically for CO2 compression. The principal advantage of Ramgen's shockwave compression, based upon proven supersonic aircraft inlet design (Fig. 2), is that it can achieve high compression efficiency at very high singlestage compression ratios.

The result is a product that lowers both capital and operating costs in a smaller footprint.The Ramgen concept requires only two stages of compression, with a matched set of independent-drive, single-stage compressors instead of a conventional integral gear compressor configuration with a common bull gear drive. Each of the Ramgen stages can achieve a pressure ratio of ~10.0+:1.

An intercooler is used between the low-pressure (LP) and high-pressure (HP) stages, and an after-cooler is used after the HP stage. The high-pressure stage is shown below, along with a typical T-s diagram for the Ramgen two-stage configuration.

The stage discharge coolers can be the CCUS process itself. Cost effective heat integration, enabled by the high quality heat of compression associated with the 10:1 compression ratio, can substantially improve the economics of CCUS. The Ramgen LP and HP stages can provide 270 Btu/lb- CO2 to a variety of heat integration options.

It should be noted that eight- or 10-stage designs are sensitive to a two-phasing effect, because the margin between the compressor-stage discharge pressure and the two-phase region in and around the critical point (shown in red below) is small and somewhat unpredictable depending on gas impurities. The proximity of the line of a constant 100°F

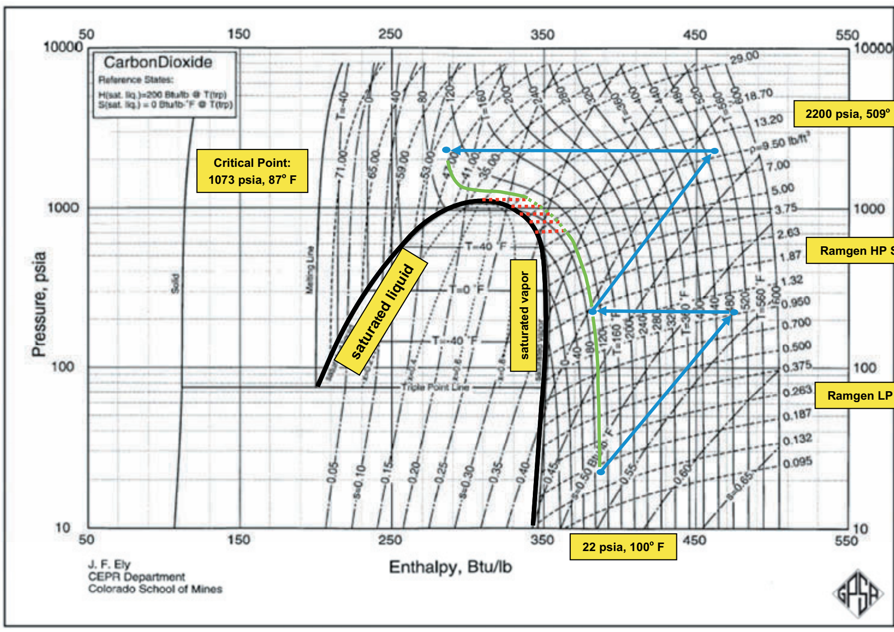


*Figure 4 - Ramgen CO2 pressure-enthalpy diagram*

(38°C) temperature to the CO2 vapor dome in the pressure-enthalpy diagram (show in green) illustrates the challenge of fully inter-cooling the later stages of multi-stage designs. Ramgen (shown in blue), on the other hand, operates in regions very much removed from the critical point.

Ramgen and Dresser-Rand plan to develop a series of frame sizes to support both amine-based and ammonia-based capture technologies, as well as other emerging capture technologies. The planned frame sizes would be able to support a full capacity 800 MW power plant using a single set of Rampressor units.

## Ramgen's Competitive Advantage

Ramgen's technology has both capital and operating cost advantages.

- Ramgen expects to be 50-60 percent of the conventional integrally geared centrifugal compressor on an installed cost basis.

- The Ramgen two-stage configuration will require approximately the same shaft input power as the eight- or 10-stage equivalent when inter-stage temperatures and pressure drops associated with intercooler are included.

- Heat recovery can be of significant value when fully integrated at scale. The Ramgen two-stage configuration has a nominal discharge temperature of 500°F (260°C) vs. conventional integrally geared designs of 200°F (93°C).

- The Ramgen design can take advantage of colder inlet temperatures and resulting lower power consumption, if available. The Ramgen inter-stage pressures are nowhere near the critical point on the pressure enthalpy diagram and the associated two-phase concerns. Ramgen may be able to run colder inter-stage temperatures, which could further enhance its efficiencies.

- Shock compression is a near-instantaneous phenomenon. As long as the discharge pressure is above the critical point on the pressure enthalpy diagram of all the constituents in the gas mix, concerns over two-phase flow should be minimized.

- The two-stage intercooled log mean temperature difference (LMTD), a key determinant of the cooler surface area required, will be three times that of the integral gear designs resulting in coolers that require one-third of the surface area to achieve the same cooling effect.

- Ramgen's design will have a substantially smaller footprint.

- High power drives are of limited availability and expensive; Ramgen's independent drive configuration should allow for improved motor selection options.

## Test Validation of Aerodynamic Performance

Ramgen and Dresser-Rand are currently preparing for a test of a 10:1 pressure ratio, 10,700 HP (8 MW) CO2 unit with a 2,215 PSIA (152 bar) discharge pressure. The unit is being assembled for testing on a dedicated 13,400 HP (10 MW) closed loop CO2 test facility at Dresser-Rand Olean Operations. The goal is to validate aerodynamic performance, as well as operating characteristics and mechanical integrity. The test facility is currently being qualified, and testing is expected to begin later this year.

Additionally, Ramgen and Dresser-Rand are currently in the process of developing a family of supersonic compressors to serve the CO2 market. Development is expected to be complete in early 2014. The high-pressure ratio-per-stage capability of the Ramgen technology is the key enabler needed to achieve this goal. The technology concept addresses the two key objectives identified by the U.S. DOE for the capture and storage of CO2 – lower cost and improved efficiency.

### More information

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# Advanced compression technology for CCS, EOR, refrigeration and vapour

This paper gives an overview of advanced, innovative and proven technologies for CO2, N2, propylene and vapour compression. This includes reciprocating and centrifugal compression - with focus on innovative gear type designs for onshore applications - in comparison to other technologies. This comparison is related to demands for upcoming Enhanced Oil Recovery (EOR), CCS, Coal Gasification (IGCC, Oxyfuel), refrigeration processes, vapour re-compression and an outlook to offshore high pressure CO2 compression.

**By Dr. Rolf Habel, MAN Diesel & Turbo SE**

Compression of CO2, N2, Propylene and vapor has a long tradition in modern industrial processes and furthermore plays an increasing role in the present discussion of the world wide climate change. Especially in refinery and food industry applications it is used and a common good since several decades. Nowadays numerous industrial procedures require them not in a gaseous but in a compressed state at a specific pressure and temperature.

The use of high-speed reciprocating compressors for Sequestration (CCS) or Enhanced Oil Recovery (EOR) is the historical and traditional approach for the manufacturing of compressed CO2. Nevertheless recent investigations reveal several limits of this technology – e.g. the upper capacity of possible flow rates have strong restrictions due to the mechanical design.

For this reason centrifugal type compressor systems are now state of the art and a promising solution for future CO2 projects. Centrifugal compressors generally can be split into two major building types which distinguish by design namely single-shaft (in-line, between bearings) centrifugals and multi-shaft integral-gear centrifugals. These assembly alternatives will be compared in this paper.

MAN Diesel & Turbo has manufactured reciprocating compressors in the past and still is manufacturing both types of centrifugal technologies (single-shaft and multi-shaft type, according to API 617 as stated by MACEYKA, PICKEREL in 2007) for CO2 services. We therefore feel confident and in a position to give a sophisticated overview and comparison of all technologies.

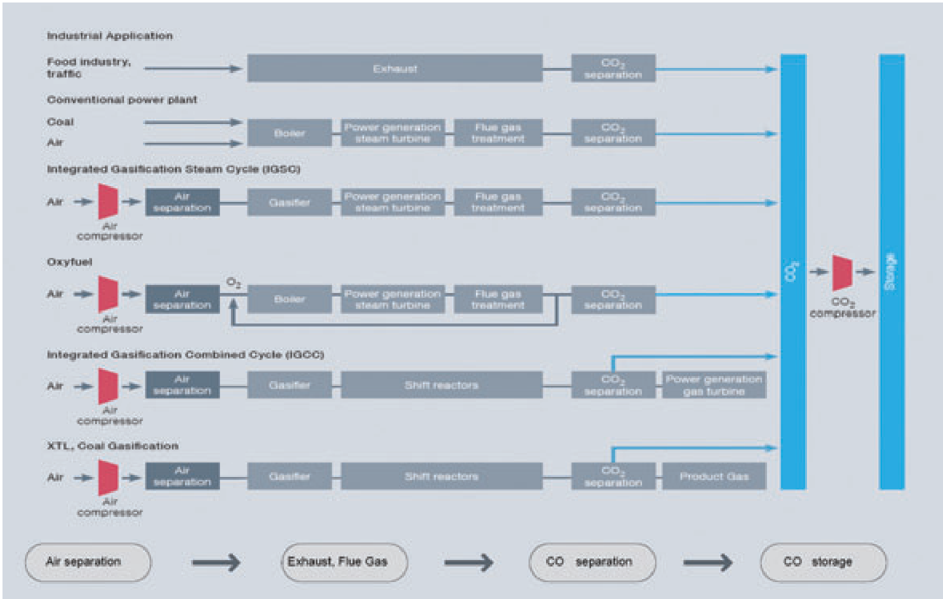


*Figure 1 - process overview*

## Conventional CO2 Technology (Recips and centrifugal compressors)

For Food Industry, Refineries, Sequestration (CCS) or Enhanced Oil Recovery (EOR), the traditional approach to CO2 compression has been to use high-speed reciprocating compressors. The main reasons for this are:

- Flexibility with regards to pressure ratio, and capacity (if equipped with variable speed drive or valve unloaders)
- Short delivery times, since many recip. packagers dispose of a selection of frames and cylinders on stock, and can assemble a package in a few months
- Light-weight skid-mounted units can be relocated at will
- Familiarity of the field operators with these machines and their suppliers

A number of factors however favor using centrifugal compressors for such application (BOVON & HABEL, 2007):

- The capacity of most CO2 recovery schemes today exceeds the range of reciprocating compressors (max. 12 kg/s)
- Reciprocating compressors are maintenance intensive
- The high density of CO2 may cause problems with high velocities (valves)
- Slow speed recips. require massive foundations - resulting in high capital and operating costs

By comparison, centrifugal compressors offer:

- Higher capacity, volume flows are possible (up to ~ 100 kg/s)
- Superior efficiency
- Oil-free compression
- Higher speed, better matched to the high-speed driver (electric motors or steam turbines) commonly used in the 10-40 MW range
- By design, they are less maintenance-intensive, leading to considerably extended intervals between overhauls

## Proven Gear-Type technology for innovative onshore CO2 projects (EOR and CCS)

Within the centrifugal compressor markets, there are still 2 technologies, namely single-

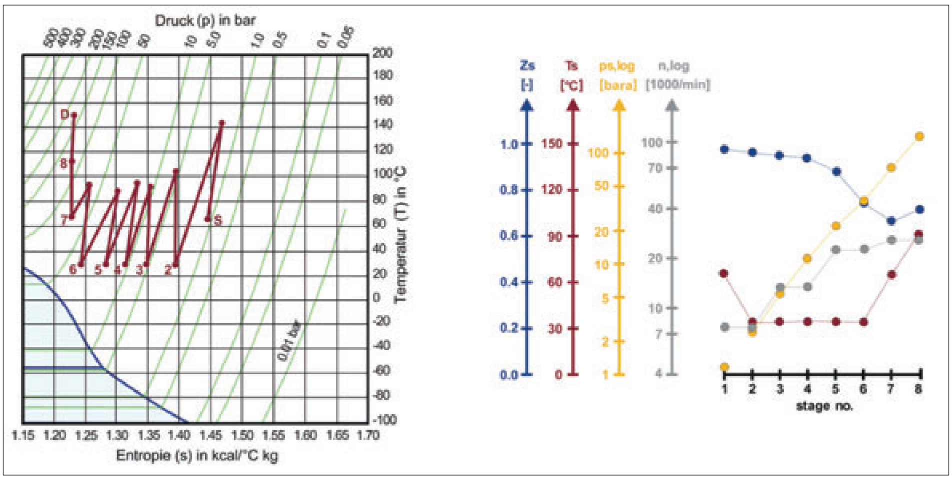


*Figure 2 - T-s Diagram of 10 stage compression process with intercooling*

shaft (in-line, between bearings) centrifugals and multi-shaft integral-gear centrifugals. MAN manufactures both and has applied both in CO2-Service. We come to the conclusion, that for most high flow onshore CO2 applications, the multi-shaft integral-gear design offers undeniable advantages:

Higher efficiency, thanks to:

- Optimum impeller flow coefficient, due to the fact that optimum speed can be selected for each pair of impellers
- Axial in-flow to each stage
- Shrouded or unshrouded impellers can be used
- Small hub/tip ratio
- Intercooling possible after each stage (impeller). See Figure 9: Mollier Chart for CO2 with marked pressure lines for 100 and 220 bara.
- External connection after each stage gives more flexibility in selecting the pressure level for the dehydration system, if applicable
- Contrary to in-line compressors, there is practically no limit to the possible number of stages in one machine (pressure ratio of 200 is possible on a single frame)
- Integral-gear compressors can be direct-driven by a 4-pole electric motor on the bull-gear, or a steam turbine on one of the pinions

All the features of these machines are well-proven and many references exist in various services and frame sizes:

- Design is existing for 30 years and more
- Engineered units can be built up to 10 stages (5 pinions). Unit power range up to 30 MW is commonly used, for instance in air separation plants
- Can be equipped with all the current range of sealing systems
- Integral-gear compressors now recognized by API 617
- Reliability and interval between overhaul considered comparable to in-line design

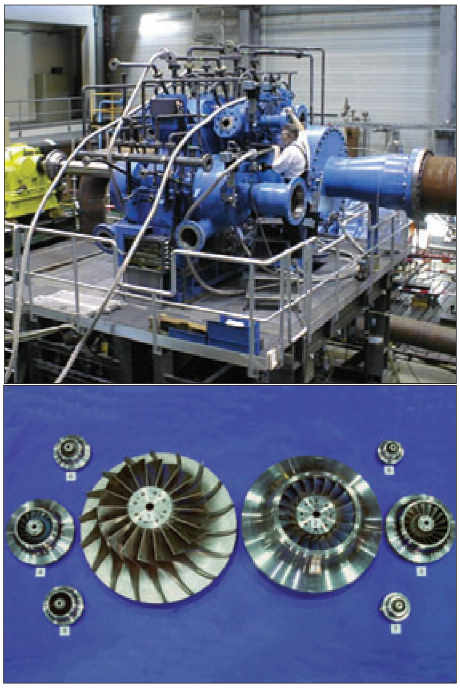

*Figure 3 - RG80-8 during testing (top); Impellers of RG80-8 in North Dakota (bottom)*

MAN has delivered several integral-gear compressors for CO2-Service with up to 10-stages. References are:

**• 8-Stage CO2 compressor RG 80-8 for coal gasification plant in North Dakota, CO2 is used for EOR in Weyburn Oil-fields -** two units commissioned in 1998, with an additional train in 2005

- Pressure from 1.1 bara to 187 bara
- Massflow ≈ 34 kg/s
- Impeller diameters 800mm – 115 mm
- Pinion Speeds 7350 – 26600 1/min
- Driven by fixed-speed synchronous electric motor

For more details on this project refer to OLSON, AMMERMANN, HAGE (2004) as well as PERRY, ELIASON (2004).

**• 10-stage CO2 RG 56-10 compressor in Russia commissioned in 1992**

- Pressure from 1 bara to 200 bara:
- Massflow ≈ 13 kg/s
- Impeller diameters 550mm – 90mm
- Pinion speed 26000 – 48000 1/min
- Driven by fixed-speed asynchronous electric motor

**• 8-stage CO2 compressor RG 40-8 in Slovakia commissioned in 2002**

- Pressure from 1.1 bara to 150 bara
- Massflow ≈ 8 kg/s
- Impeller diameters 400mm – 95mm
- Pinion speed 8000 – 41000 1/min
- Driven by variable speed asynchronous electric motor

**• 8-stage compressor RG 56-8 in CIS commissioning in 2011**

- Pressure from 1.1 bara to 150 bara
- Massflow ≈16 kg/s
- Impeller diameters 500mm – 95mm
- Pinion speed 8000 – 36000 1/min
- Driven by steam turbine

## Technology Comparison and further Innovations and Improvements

In Table 1 different technologies for CO2 compression services are compared. It shows that gear type centrifugal compressors display better efficiency and lower power usage when compared to inline centrifugal compressors, reciprocating compressors and a new shock waves technology, which is in a developing/research stage by the company RAMGEN Power Systems. However this gear type technology for HP CO2 is by now only proven for onshore applications.

For this reason the authors` opinion is that the multi-shaft design is in total the superior technology for industry applications, based on the good experience and proven field references.

The latest result of MAN development is the extension of the multi-shaft product line for high volume flows in a fully engineered RG100. For this reason MAN can now offer the following flows with their existing and proven gear type product line according to Table 2.

In Figure 4 a typical design of a 4-stage integrally gear type compressor is shown. In Figure 5 a typical performance curve of an RG100-8 is displayed.

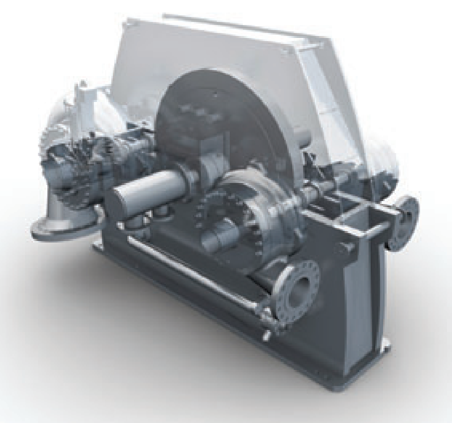

*Figure 4 - 3D Model of a 4 stage integrally-geared RG – Compressor*

| | MAN Diesel & Turbo | Competition Offering | MAN and Competition Offering | Competition Offering Developing |
|---|---|---|---|---|
| **Characteristics** | Estimated values by MAN Turbo | | * | * |
| Technology | Integrally Geared Turbo RG63-6 | Piston type Reciprocating compressor | Inline Process Turbo | Shockwave |
| Size without coolers approx. (m) | 5 x 4 x 3 | - | 7.6 x 3 x 3 | 1.8 x 3.7 x 2.5 |
| Compression Ratio per Stage | 2.1:1 | - | 1.6:1 | 10:1 |
| Estimated Weight (tons) Compressor on skid | 80 | - | 280 | 32 |
| Massflow (kg/s) | 19.3 | **Max flow limited to ~ 12** | 19.3 | 19.3 |
| Total Compression Ratio | 100:1 | - | 100:1 | 100:1 |
| Number of Compression Stages | 6 | - | 12 | 2 - 3 |
| Possible number of Intercoolers | 5 | - | 2 | 1 |
| Casings | 1 | - | 3 | 1 |
| Estimated kW | **6,200** | - | **8,300** | **7,300** |
| Isothermal Effeciency (%) $\eta_p$ | 80 | - | 60 | 66 |
| Approx. Avg. stage/ Casing Discharge Temperature (°C) | 100 | - | 190 | 240 |
| | | | | |
| **Economics** | | | | |
| CAPEX | LOW/MEDIUM | MEDIUM | HIGH | ? |
| OPEX | LOW | HIGH | HIGH | ? |

*Ramgen Power Systems, Carbon Management Conference, May 2007

*Table 1: Comparison of different CO2 compression technologies*

## Conclusion

In conclusion and based on our experience, for volume flows > 12 kg/s and pressures up to 250 bar integral-gear compressors have definite advantages over reciprocating or supersonic technologies and in-line centrifugals in most CO2 services and as well for N2 compression, several special cooling processes and vapor recompression. Over 250 bar and offshore the barrel type design is state of the art.

- Gear type compression is more efficient than supersonic or reciprocating technology (see Table 1)
- In-line compressors require approx. twice the number of stages than integral-gear compressors, leading to one or two additional casings
- Integral-gear compressors show higher efficiency
- Integral-gear compressors have comparable maintenance requirements as in-line compressors
- Barrel type design is better referenced for pressures > 250 bar and offshore applications

Based on the individual project demands a proven, reliable, and cost effective solution for advanced compression can be chosen.

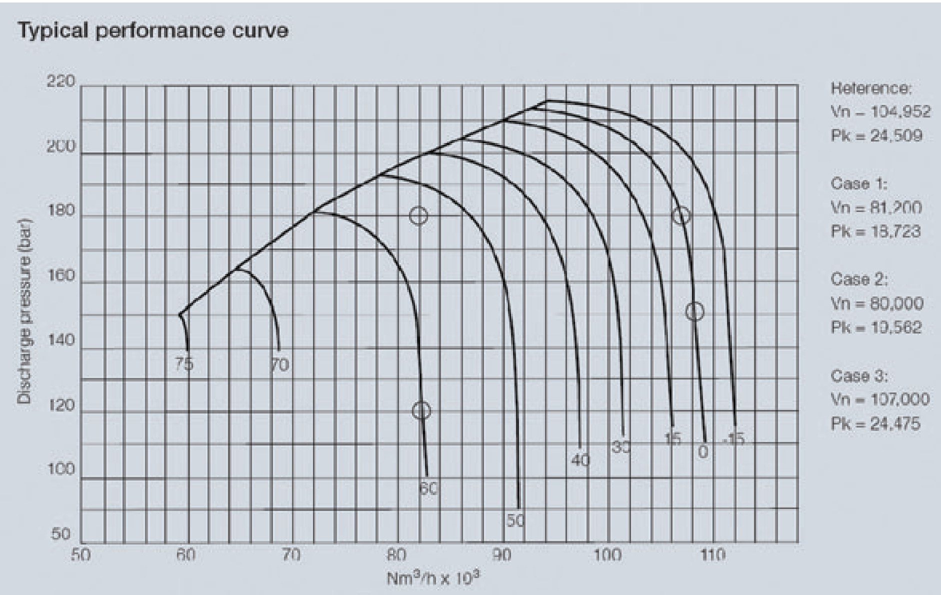


*Figure 5 - typical performance curve for a RG100-8 compressor*

| Type | RG45-8 | RG80-8 | RG100-8 | 2xRG80-8 | RG140-8 |
|---|---|---|---|---|---|
| $Nm^3/h$ | 20,000 | 65,000 | 120,000 | 130,000 | 205,000 |
| $Am^3/h$ | 27,000 | 70,000 | 130,000 | 140,000 | 245,000 |
| Kg/s | ~ 12 | ~ 34 | ~ 66 | ~ 68 | ~ 110 |
| Power | 5 MW | 14 MW | 25 MW | 28 MW | 45 MW |
| $P_s$ (bara) | 1.1 | 1.1 | 1.1 | 1.1 | 1.1 |
| $P_d$ (bara) | 140 | 200 | 215 | 200 | 215 |

*Table 2: Overview over typical sizes and flows*

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## More information

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Further publications and information can be found here:
www.mandieselturbo.com

# UK CCS Research Centre opens

The UK CCS Research Centre, which opened in April this year, will hold its inaugural meeting in Durham in September.

The UK CCS Research Centre was established in April with funding from the Engineering and Physical Sciences Research Council (EPSRC - £10M), the Department of Energy and Climate Change (DECC - £3M) and member organisations (£2M). Since then it has literally made a RAPID start, as academics and industry experts have worked to produce the first version of its research planning guide, the Research and Pathways to Impact Development (RAPID) Handbook.

RAPID begins by looking in detail at the knowledge and related capacity that will be needed to implement a wide range of different CCS applications and also to what extent this knowledge is already available to users. This makes it easier to identify specific research needs and how the results can best be used to make an impact on CCS delivery. Nineteen separate applications, including full systems analysis, many types of capture technology, pipeline and shipping transport, storage and cross-cutting legal, environmental, social and economic inputs to CCS projects are covered in this first version of the RAPID Handbook, which is free to download from the Centre's website ().

Professor Jon Gibbins, the Centre Director, is particularly grateful for the help from industry CCS experts in the RAPID exercise, "since DECC's new CCS Commercialisation Programme launched at the same time as the Centre, everyone has been very busy. So we academics in the UK CCS Research Centre really value and appreciate the time that industry colleagues were able to spend with us looking in detail at how CCS research might be applied."

The Centre launched its first call for proposals from the UK academic community in July with the help of its newly established Board, chaired by Philip Sharman. Up to £1.5M is available to fund research projects highlighted by RAPID that address priorities identified by the Advanced Power Technology Forum (APGTF) and the DECC CCS Roadmap for Innovation and R&D.

The UKCCSRC Pilot-scale Advanced Capture Technology (PACT) Facilities, set up with contributions from DECC and RWE npower, are being commissioned on a site near Sheffield. PACT will offer one site for a unique set of pilot-scale combustion, gasification and post-combustion capture facilities that can operate in a wide range of modes. It will be the focal point for larger scale experimental work undertaken by UKCCSRC and will also be available for use by UK industry, including SMEs, for development and demonstration of products for the CCS supply chain..

Other major research opportunities are expected to emerge as part of the UK's CCS Commercialisation Programme. Links with overseas projects, particularly onshore injection trial sites which the UK cannot readily provide, are also being pursued.

The Centre is a virtual organisation bringing together academics, industry, regulators and others in the sector to collaborate on analysing problems and undertaking advanced research. Centre membership, based on CCS experience developed in about £50M of research projects, now stands at over 150 and is still growing. A key priority is to support the UK economy by driving an integrated research programme that is focused on maximising the contribution of CCS to a low-carbon energy system for the UK. Current central funding runs for 5 years and this will be supplemented by further support from a range of sponsors for specialised research projects; for example a new EPSRC call for projects on engineering aspects of CO2 storage has just been issued: www.epsrc.ac.uk/funding/calls/open/Pages/carboncapture.aspx

*UKCCSRC Coordination Group Members and Board Chair, Philip Sharman, at the official launch of the RAPID Handbook by the Sheffield and Tinsley Canal. (PACT offices at top of the tall building in the background.)*

If you would like to find out more about becoming a member of the UK CCS Research Centre, please fill out a membership & mailing list form online. The website also includes further information on RAPID, the PACT Facilities and UK CCS research.

Registration for the 19-20 September biannual meeting and UK CCS Research Centre launch is available online (see below)

Attendance is open to anyone with a legitimate interest in CCS, although priority will have to be given to UKCCSRC members and network associates if space is limited.

## More information

www.ukccsrc.ac.uk

Register for the event:
www.ukccsrc.ac.uk/meetings-events

# ROAD project - lessons learned

The report highlights a number of key learning points that will allow the project to continue successfully through future phases, and which may prove valuable for other CCS projects in the future.

A report into the Rotterdam Opslag en Afvang Demonstratie (ROAD) project has delivered a number of conclusions.

**It was found that a solid understanding of permitting procedures and scheduling can have a significant impact on timing and funding constraints.** Anticipating delays in agreeing draft permits for public consultation, and building these delays into the project schedule would help avoid any delays in agreed milestones; for example, a final investment decision.

The nature of this project as a technical demonstration of a new technology must be noted as having a unique impact on the permitting procedure that is likely to result in challenges through various aspects of the procedure, from permit application to public consultation. In addition to this, the impact of any project delay could have further consequences on funding that may be conditional on achieving certain milestones.

Time, budget and space constraints have led to solutions that are not fully optimized with respect to technical decisions and energy usage. For a new power plant with full scale carbon capture, many technical concepts can lead to further performance improvement and savings in investment and operational costs.

Considering the current market conditions and the expected plant operation modes for grid support, the steam pressure will fluctuate with load. ROAD has been limited in design optimization for off-design performance of the capture plant. One of the major questions ROAD will be able to answer when operating the demo-plant, is its reaction and behavior when lower steam pressure is available.

**Independent process model validation using pilot plant data has been particularly valuable.** It would be much riskier for a company to develop a post-combustion capture project without undertaking independent process model validation combined with access to pilot plant performance data. However, current pilot plants are not optimized for demonstrating low emission performance.

Therefore care should be taken when interpreting the results especially when extrapolating them to full scale. Appropriate independent process modeling expertise using pilot plant data is valuable in reducing risks associated with extrapolation of pilot plant data. Using pilot plant data in process models is also a key risk mitigation strategy for estimation of operating costs (i.e. parasitic energy usage).

**For transport and storage it is important to define the specifications for the CO2 product.** Parameters like oxygen, water and dust (amount and particle size distribution) are the most important. The CO2 specifications differ widely for different capture technologies and due to lack of experience it is not known what is acceptable for pipeline, well and reservoir. A significant insight of the flow assurance study was the conclusion that a two-phase flow will occur in the pipeline and in the well (at least the top of the well), during start-up.

Transporting a fluid with two phases is a challenge; this can lead to severe slugging effects which will lead to vibrations. Also, the design of the CO2 compressor was a challenge. It seems there are a few companies able to build a large CO2 compressor combined with the demanded wide operational envelope. Furthermore, modifying a satellite platform with limited space provides challenges because limited space is available. Also the integrity of the existing platform is an attention point.

**In addition, important lessons were learned with regard to the integration of CCS and a power plant.** Productive cooperation between the power plant and CCS teams is essential. A key learning point for the project in this regard was the importance of the utilities agreement between Maasvlakte CCS Project (MCP) and Maasvlakte Power Plant Unit 3 (MPP3).

**Support and involvement of local, regional and national governments throughout all project phases, as well as a positive public perception, are a prerequisite for creating the right circumstances for the successful implementation of a CCS project.**

Since CCS is a technology under development, a specific legal and regulatory framework on capture, transport and storage technologies is in many countries still missing or in development. This demands pro-activity, flexibility and close interaction with regulators and authorities.

Managing expectations of stakeholders and developing a clear project vision are a prerequisite in that regard. One of the biggest threats is losing track of stakeholders' views and interests. Instead CCS projects should develop an outside in perspective, taking into account stakeholder expectations. By developing a stakeholder dialogue they create two-way communication with stakeholders that are relevant to the implementation of the project.

As a consequence of diverse technologies in the CCS chain, spread over different areas, multiple governments and authorities are involved in the projects. This demands an integrated Stakeholder Management approach comprising functions such as regulatory affairs, permitting and public outreach. Ultimately Stakeholder Management is instrumental in creating necessary conditions for other project functions (e.g. capture, transport & storage).

**The fact that the project is carried out in a joint venture has had a generally positive impact.** Combining the knowledge and methodologies of two parent companies, assumptions are challenged more rigorously, group thinking is avoided and decisions are taken more objectively. The existing knowledge within the parent companies is crucial in all aspects of the technical and commercial activities. Knowledge sharing between the project team and the parent companies is crucial. However, working in an innovative joint venture project also poses some challenges.

The ROAD construction schedule is driven by both the MPP3 construction schedule and cost minimization. In order to avoid MPP3 outage penalties, the tie-in works have to be executed on-track. Both drivers led to the specific construction plan and the clustering of heavy lift components. Thanks to the clustering of heavy lift components the cost and project schedule can be squeezed significantly. After the lifting and placement of these major components the capture plant can be assembled. In a second phase the transport and storage works will become a point of attention.

**The cooperation with the Global CCS Institute has proven instrumental in reaching the wider CCS community.** ROAD has received valuable comments on draft Special Reports, all of which we believe today form an excellent bundle of practical information for setting-up a large scale CCS demonstration Project. ROAD is looking forward to continuing this cooperation in the future.

### More information

www.road2020.nl
www.globalccsinstitute.com

# CCS in Europe - the way forward

The priorities have changed since the inception of the CCS project and the EU should look again at its energy policy to ensure that the best solutions for Europe's energy future have the chance to develop, says Agata Hinc, Managing Director, demosEUROPA – Centre for European Strategy

It was John Maynard Keynes who said, "When the facts change, I change my mind". These words should resonate with anyone who runs a multiannual project and are very much true for the "CCS project" of the European Union, says Agata Hinc in the report, "CCS in Europe - the way forward".

The project itself seemed to be one of the best solutions to the challenge of climate change back in 2007 when Europe was shaping its current energy and climate policy and in 2009 when the EU CCS Directive was published. The facts have changed since then and this means that the EU should rethink its strategy regarding the role of CCS in decarbonising the EU economy. There are at least four new facts that should be taken into consideration in this respect.

### Fact one - the political momentum is gone

At the very beginning of this century there seemed to be a consensus among key political stakeholders that very ambitious energy and climate goals were needed. Back then there was a common understanding that fighting climate change was one of the biggest challenges facing the world and that it was Europe who should become a leader of this fight regardless of the costs.

Now, the political momentum for CCS is not there any more. Political leaders had to redirect their priorities toward the burning issues of economic instability and fiscal cohesion in Europe.

What is more, the regulatory regime enabling safe CO2 storage (a condition for implementation of any CCS full scale project) has not been transposed in most EU member states and the deadline expired on 25 June 2011. Only eight EU countries have completed the implementation of the EU CCS Directive.

### Fact two – most of the EU CCS demo plants will not meet the 2015 deadline

The ROAD (Rotterdam Opslag and Afvang Demonstratieproject) project seems to be the only one (of all EU CCS demo plants) that is really progressing. Most probably, this will be the only EU CCS demo plant that will not be delayed and will start operating in 2015.

The project, which is expected to cost €1.2 billion was awarded funding of up to €180 million from the EC and it has an additional €150 million from the Dutch Government, and hopes to make a final investment decision soon.

### Fact three – funding for CCS is not sufficient

There are a number of obstacles that all EU CCS demonstration plants have been facing. They are (in most cases): a lack of regulatory regime, a low level of public acceptance and a problem with ensuring financing for the total project costs. The last one seems to be the most challenging.

Assuming that the average cost of an EU CCS demonstration plant can be estimated of about €1.5 billion and knowing that all the projects have been awarded €180 million (the Italian project received a bit less €100 million) from the EERP – this means that each project has roughly 12% of its costs secured.

### Fact four – a new gamechanger occurred

The Energy Roadmap 2050 had the advantage of being released 9 months after the Low Carbon one and it identified "new" possible transition technologies for carbon intensive economies that have become available in the European market very recently. Shale gas is one of them.

The Energy Road-map very clearly illustrated that the switch from coal to less carbon intensive fuels (i.e. shale gas) can be not only less painful, but also it could be of a benefit to coal-dependent countries (like Poland) and at the same time to the energy and climate policy of the European Union. Shale gas became a game changer not only with respect to energy and climate policy, but also with respect to the energy security issue in Europe and therefore should not be underestimated.

## The way forward

If CCS is to happen (globally), its demonstration phase needs to be completed soon – literally, there have to be full scale integrated CCS demonstration plants operating on the ground, that would test the effectiveness and economic viability of the whole CCS chain – capture, transport and storage (both offshore and onshore).

There seems to be three basic scenarios for the European Union to go forward with its "CCS project":

**Scenario 1. Business as usual**
In this scenario, the EU stays with the current policy approach and the regulatory and financial regimes and hopes for the best.

**Scenario 2. Reshaping the CCS policy**
In this scenario, the European Union reshapes its current CCS policy and makes it more effective.

**Scenario 3. Changing the EU energy and climate policy priorities**
In this scenario, the European Union decides to refocus its climate and energy policy.

## Conclusions

As far as the emissions reduction potential is concerned, no better technology than CCS has been found that could reduce CO2 emissions from burning fossil fuels in a substantial manner.

As far as the economic potential is concerned, it has been proven that innovative low carbon technologies can help stimulate future growth of the EU and there seems to be a common agreement that Europe wants to use these technologies for that purpose.

There are two key ways of decarbonising Europe: (1) switching from coal to other (less carbon-intensive) energy sources (i.e. renewables, gas), (2) make use of clean coal technologies. Both options might be combined and will almost certainly have to be. This view is confirmed both by the "Roadmap for moving to a low-carbon economy in 2050" (March 2011) and by the "Energy Roadmap 2050" (December 2011).16

Europe is at energy crossroads and its future energy mix and energy supply chains are uncertain. Because of this, some important decisions on the development of different energy technologies need to be taken sooner rather than later. This does not imply that the EU should choose the winners (the energy technologies of tomorrow) now, but it should ensure that the technologies with the biggest potential to deliver the common goals have foundations to develop. If the current way of ensuring these foundations is not effective enough, there is not only a need for but also a duty of the EU decision- and policy-makers to change it.

### More information

www.demoseuropa.eu

# UK government publishes CCS innovation needs assessment

## The UK Department of Energy and Climate Change (DECC) has released a Technology Innovation Needs Assessment (TINA) which says CCS could reduce UK energy costs by £10-45bn to 2050

The TINA examines the potential for innovation in CCS technology and assesses the economic benefits to the UK. A much more detailed TINA analysis pack will be published separately, said DECC.

Innovation across the CCS technology chain could reduce UK energy system costs by £10-45bn1 to 2050, says the report, and innovation to ensure the security of long-run CO2 storage remains particularly critical to CCS viability.

Innovation can also help create a UK industry with the potential to contribute further economic value of £3-16bn to 2050. Significant private sector investment in innovation, catalysed by public sector support where there are market failures, can deliver the bulk of these benefits with strong value for money.

### What are TINAs?

The TINAs are a collaborative effort of the Low Carbon Innovation Co-ordination Group (LCICG), which is the coordination vehicle for the UK's major public sector backed funding and delivery bodies in the area of 'low carbon innovation'.

The TINAs aim to identify and value the key innovation needs of specific low carbon technology families to inform the prioritisation of public sector investment in low carbon innovation. Beyond innovation there are other barriers and opportunities in planning, the supply chain, related infrastructure and finance. These are not explicitly considered in the TINA's conclusion since they are the focus of other Government initiatives, in particular those from the Office of Carbon Capture and Storage in DECC and from BIS.)

The TINAs apply a consistent methodology across a diverse range of technologies, and a comparison of relative values across the different TINAs is as important as the examination of absolute values within each TINA.

### Key findings of the TINA

**Potential role in the UK's energy system**

- CCS offers many benefits to a low-carbon energy and economic system: (i) it allows the flexibility and energy security benefits of fossil fuel combustion with near-zero GHG emissions; (ii) when applied to biomass firing, it serves as a source of relatively low-cost negative emissions; (iii) it is applicable to industrial power and process emissions, which are particularly costly to reduce.

- Energy system modelling suggests that electricity generation with CCS could deliver c.10-35% of total generation by 2050, with c.11-60GW in capacity. This depends primarily on public acceptance of alternatives (wind and nuclear), the availability of biomass, and the overall energy demand. The application of CCS to industry offers further deployment potential, but is not assessed in this report.

- Having CCS available (compared to an energy system without CCS) is estimated to save the UK hundreds of billions of GBP in cumulative value between 2010 and 2050. Nevertheless, considerable work remains to demonstrate CCS at large scale and across the entire chain (capture-transport-sequester-secure), and widespread deployment is unlikely prior to 2020.

**Cutting costs by innovating**

- The key technological components of carbon capture, transport and injection have been demonstrated at commercial scale, however, component costs and efficiency penalties remain high and uncertain, and many challenges related to full integration remain to be tackled.

- Full-scale, source-to-sink demonstration is particularly urgent to prove scalability of CCS, and its long-run availability to the system. Moreover, it is necessary to drive cost-reduction opportunities related to full plant integration, and to identify the most important component technology innovations.

- Critically, the assurance of very long-term CO2 storage with a very high degree of certainty is still unproven. This constitutes a significant risk to the viability of CCS and its rapid roll-out in the near to mid term. Innovation has the potential to drive down the costs (ignoring fuel) of conversion with capture by 15% by 2025 and 40% by 2050. Innovation can further reduce the long-run costs of transport by ~50% and of storage by >50%.

- Innovation in measuring, monitoring & verification (MMV) and mitigation & remediation (M&R) can ensure the security of sequestered CO2, reducing the financing costs of CCS, as well as enabling its overall availability as an abatement option.

- Successful innovation could reduce the costs to the UK of CCS deployment by £10–45bn to 2050.

- On top of this, >>£100bn in systems savings would result from CCS availability (by reducing the need for more expensive alternatives).

**Green growth opportunity**

- UK suppliers could play a significant role in the global CCS market, with a 4-6% share of a market with potential cumulative gross value-added of between £150 - 750bn up to 2050.

- If the UK successfully competes in a global market to achieve the market share above, then the CCS related industry could contribute £3 – 16bn to UK GDP up to 2050 (with displacement effect).

**Potential priorities to deliver the greatest benefit to the UK**

- Innovation areas with the biggest benefit to the UK are (i) deep sea storage, MMV and M&R; and (ii) advanced capture development (especially gas and biomass) and demonstration of integrated conversion-capture. In both, the UK should look to lead or join multi-national partnerships

- Given specific niche strengths, there is also a case for broad "open call" support for leading ideas with "breakthrough" potential (e.g. novel capture or compression concepts, etc.)

- Supporting all of the UK‟s priority innovation areas would require hundreds of millions of GBP over the next 5-10 years (leveraging 2-3 times that in private sector funding). The UK is addressing some of these innovation areas, but there remains considerable scope to expand this activity.

### More information

www.decc.gov.uk

# Policy, company and regulation news

## CCS research centre opens in Australia

www.co2crc.com.au

**The Peter Cook Centre for Carbon Capture and Storage Research has opened in Victoria, Australia.**

The Cooperative Research Centre for Greenhouse Gas Technologies (CO2CRC) will direct research at the new Centre, which has been sponsored by Rio Tinto with $3 million in funding over 3 years.

A further $3 million in Rio Tinto funding over 3 years will support the CO2CRC Otway Project, Australia's first demonstration of geological carbon dioxide storage, as a field site for carbon storage research.

"The Peter Cook Centre for CCS Research will integrate CO2CRC research capabilities at the University of Melbourne, forming a world class hub for research into this important technology," said Dr Richard Aldous, Chief Executive of CO2CRC.

"The Centre brings together professors and researchers from a wide variety of disciplines, including the chemical and process engineering associated with capturing CO2 from power plants, and the geology and geomechanics required for storage of carbon dioxide in deep rock formations. The complementary work at the Otway Project is helping develop the tools and methods to ensure CO2 is safely stored and monitored."

"Building this kind of critical mass in an Australian research centre is vital to the national development and deployment of large-scale CCS, which will be a major part of Australia and the world's drive to manage climate change."

Incorporating extensive research already underway at the University of Melbourne, the Peter Cook Centre for CCS Research will initially host over 30 scientists working on CCS, including a recently funded Professor of Carbon Storage supported by the Victorian Government.

The Centre, named for the eminent geologist and founder of CO2CRC Professor Peter Cook, will link researchers with the CO2CRC Otway Project Subsurface Storage Laboratory, which has been safely storing carbon dioxide deep underground since 2008.

Rio Tinto Chief Executive Energy, Doug Ritchie, said today's announcement was an important one for Australian science.

"Rio Tinto believes carbon capture and storage will be a significant technology globally, and one with a particular resonance for Australia given the role of coal as our major source of electric power, and our position as a major international supplier of fossil fuels," Mr Ritchie said.


*Launching the Peter Cook Centre for Carbon Capture and Storage Research. Left to right: Minister Michael O'Brien (Victorian Minister for Energy and Resources), Richard Aldous (CEO, CO2CRC), Doug Ritchie (Head of Energy, Rio Tinto) and Professor Jim McCluskey, (Deputy Vice-Chancellor (Research) University of Melbourne)*

"CCS will be the only way of decarbonising significant sectors of the global economy such as power generation and steel and cement manufacture but it needs further development and commercialisation. Rio Tinto is proud to contribute to this with today's $6 million announcement. There are very few projects in the world that are game changers in CCS. The CO2CRC Otway Project is one of them."

Victoria is a natural location for development of CCS, as the future of the State's large brown coal reserves is dependent on new low emission technologies. Victoria also has significant offshore CCS storage potential.

## DOE begins integrated CCUS project at Plant Barry

fossil.energy.gov

**CO2 injection has begun at the world's first fully integrated coal power and geologic storage project at Alabama Power's Plant Barry.**

The "Anthropogenic Test"—conducted by the Southeast Regional Carbon Sequestration Partnership (SECARB), one of seven partnerships in DOE's Regional Carbon Sequestration Partnerships program—uses CO2 from a newly constructed post-combustion CO2-capture facility at Alabama Power's 2,657-megawatt Barry Electric Generating Plant (Plant Barry).

It will help demonstrate the feasibility of carbon capture, utilization and storage (CCUS), assessing the integration of the technologies involved and laying the foundation for future use of CO2 for enhanced oil recovery (EOR).

In a unique process developed by Mitsubishi Heavy Industries, a small amount of flue gas from Plant Barry—equivalent to the amount produced when generating 25 megawatts of electricity—is being diverted from the plant and captured using Mitsubishi's advanced amine process to produce a nearly pure stream of CO2.

Once captured, the CO2 is transported approximately 12 miles west to the southern flank of a geologic structure called the Citronelle Dome, within the Paluxy saline formation. A pipeline was constructed for this purpose in 2011.

The Paluxy is an ideal site for injection because it is more than 9,000 feet underground and is overlain by multiple geologic confining units that serve as barriers to prevent CO2 from escaping.

Carbon dioxide injection will take place over 2 years at a rate of up to 550 metric tons of CO2 per day. Multiple monitoring technologies will be deployed to track the CO2 plume, measure the pressure front, evaluate CO2 trapping mechanisms, and ensure that the CO2 remains in the formation.

In 2017, following 3 years of post-injection monitoring, the site will be closed. At that time, the wells will either be plugged and abandoned according to state regulations, or re-permitted for CO2-enhanced oil recovery (CO2-EOR) and CO2 storage operations. If re-permitted, CO2 that would otherwise be emitted to the atmosphere would be used to recover stranded oil while also being sequestered in a geologic formation.

SECARB's Anthropogenic Test is led by the Southern States Energy Board in partnership with the Electric Power Research Institute, Southern Company, Alabama Power Company, Denbury Resources, Inc., Advanced Resources International, Inc., and other experts.

## Global CCS Institute releases five year strategy

www.globalccsinstitute.com

**The Global CCS Institute has released a draft Five-Year Strategic Plan to its international Membership.**

The Plan outlines how the Institute will continue to work both at global and regional levels to accelerate the successful demonstration and deployment of carbon capture and storage.

The Plan also outlines how the Institute will continue to develop itself as a Member-driven organisation so that it may further champion the role of CCS in reducing greenhouse gas emissions.

"In a relatively short time, the Institute has established itself as a primary channel of influence and expertise on carbon capture, use and storage" said the Institute's Chief Executive Officer Brad Page.

"Our commitment to creating a Member-driven organisation means that we must ensure continued relevance to our Membership and a financially sustainable basis for the Institute's future."

The Institute's Membership, built since its inception in 2009, currently totals 349 national and provincial governments, corporations, NGOs, research/academic agencies and industry bodies.

"Our growing Membership is testament to our solid achievements and continuing work program, and to the fact that we continue to be a global advocate for CCS," said Page.

The Institute will engage in extensive consultation with Members over the coming months to gather feedback on the Plan and forward strategy.

The Strategic Plan is expected to be finalised during 2012 with implementation to begin in 2013.

## Alberta projects get funding boost

www.ccemc.ca

**The Climate Change and Emissions Management (CCEMC) Corporation is providing $46 million in funding to support six new clean technology projects.**

The projects have a combined value of more than $327 million. The organizations receiving funding from CCEMC are:

- Cenovus Energy Inc. - $10 million for a Chemical Looping Steam Generator - 10 MW Pilot at Christina Lake near Fort McMurray
- Husky Energy - $2.9 million for the Lashburn CO2 Capture Demonstration Project near Lloydminster
- Imperial Oil - $10 million for a Cyclic Solvent Process pilot in Cold Lake
- Inventys Thermal Technologies Inc. - $3 Million for the VeloxoTherm(TM) CO2 Capture Project at Joffre
- MEG Energy Corp. - $10 million for Heavy Crude Quality Improvement in the Alberta Industrial Heartland Region
- N-Solv Corporation - $10 million for the N-Solv BEST Pilot Plant at Suncor Dover in Fort McMurray

CCEMC estimates these six projects will combine to reduce emissions by more than 183,000 tonnes over 10 years, and that does not consider further emissions reductions as technology is commercialized. The potential emissions reductions that could be realized through build out and commercialization of these technologies is estimated at five megatonnes by 2021. For every dollar CCEMC invests in these projects, about another seven dollars are also invested.

The six projects are from the CCEMC's fourth round of funding that was announced in April 2011. The maximum CCEMC funding per project for this round is $10 million.

Funding for CCEMC is collected from industry. Since 2007, Alberta companies that annually produce more than 100,000 tonnes of greenhouse gas emissions over a baseline are legally required to reduce their greenhouse gas intensity by 12 per cent. Companies have three options to meet their reduction target: improve the efficiency of their operations, buy carbon credits in the Alberta-based offset system or pay $15 into the Climate Change and Emissions Management Fund for every tonne over the reduction limit.

The CCEMC invests the money collected in clean technology. The CCEMC is now in the fourth year of operations. By the end of the 2011/12 operating year, the CCEMC expects to be involved in close to $1 billion of active projects that reduce emissions and spur innovation in clean technology and help our world move toward more sustainable practices.

## UK-Canada CCS trade mission visits campus

www.iseee.ca

**The Institute for Sustainable Energy, Environment and Economy and Carbon Management Canada co-hosted a UK-Canada trade mission focused on carbon capture and storage (CCS) on Monday, August 20, 2012.**

More than 40 people participated in an all-day meeting of presentations and discussions with 12 members of the UK delegation.

Participants included University of Calgary researchers and graduate students, officials from Carbon Management Canada, and representatives from industry and government.

The event included a tour of Calgary-based Carbon Engineering's air capture prototype machine on campus, followed by a reception at Hotel Alma, hosted by Consul General Tony Kay, the newly appointed consul general in Calgary.

The ISEEE website will feature a report on the meeting and speakers' presentations.

## ECN report supports business case for China carbon capture

www.ecn.nl

**With carbon prices at rock bottom, it may be surprising to hear that research conducted by ECN indicates that a business case for CCS in China is still within reach.**

Dutch sustainable energy research organisation ECN, with the Centre for Low Carbon Futures, The Chinese Academy of Sciences and consultancy firm Azure International have collaborated on a project to assess the potential of capturing CO2 from non-power industrial installations in the Shaanxi province of China. The CO2 can in turn be used to improve oil production in local oil fields whilst simultaneously trapping thousands of tonnes of CO2 that would have otherwise be released into the atmosphere.

Sponsored by the British Embassy Beijing as part of the China Prosperity SPF Programme, the project has identified a number of possible carbon capture utilization and storage (CCUS) projects which combine low-cost industrial CO2 capture and utilization of the CO2 for enhanced oil recovery (EOR). If implemented in accordance with international best practice on site characterization and monitoring, between 90-95% of the CO2 injected for EOR can be stored safely for geological timeframes.

The third largest fossil fuel producing province in China, Shaanxi is an important refining and chemical production hub for the nation. The project team identified 22 high-purity (>95% CO2) CO2 sources within the methanol, ammonia, hydrogen and ethylene production industries, which together release almost 65MtCO2 per year. Nine of these sources are within 150km of a suitable location for EOR, with the storage capacity in the region estimated at 200MtCO2.

"Two methanol plants were identified that each produce over 6Mt of high-purity CO2 per year," explained Tom Mikunda, who led the project for ECN. "Including the revenues of the incremental oil produced, these projects could be realised with costs as low as 5$ per tonne of CO2." Even with carbon prices at rock bottom, given policy support and a suitable regulatory framework, this initial research indicates that a business case for CCUS in China is still within reach."

## ADB helps People's Republic of China plan CCS road map

www.adb.org

**The Asian Development Bank (ADB) is assisting the People's Republic of China (PRC) in the development of a road map for CCS to help achieve the country's CO2 emissions reduction goals.**

ADB will assist the PRC in developing a detailed plan for a staged demonstration and deployment of CCS, which is an essential set of technologies to prevent climate change. CCS involves the separation and capture of CO2 and compression, transportation, and injection of the captured CO2 in a suitable underground storage.

"There is an urgent need to fast-track the demonstration and deployment of carbon capture and storage in the People's Republic of China to cut CO2 emissions from the energy and industrial sectors and achieve the country's long-term climate change mitigation goals," said Annika Seiler, Finance Specialist for Energy at ADB's East Asia Department.

Since 2008, ADB has been supporting the government's efforts through capacity development projects, studies, and financial assistance. Incomplete policy and regulatory framework, low fiscal and financial support for CCS demonstration projects, and inadequate international funding mechanisms to support projects have been identified as key barriers to large-scale demonstration of CCS in the PRC.

A comprehensive government-endorsed road map for CCS is expected to encourage more demonstration projects in the PRC. This project is set to launch at least two large-scale CCS demonstration projects by 2016, with an installed capacity to capture at least 2 million tons of CO2 per year.

ADB will also support the assessment of the potential role of oxy-fuel combustion CO2 capture, one of the three available CO2 capture technologies, in the PRC's optimal mix of CO2 capture technologies.

To fast-track CCS demonstration, necessary analyses and studies of oxy-fuel combustion CO2 capture technology will be undertaken in parallel to the formulation of the road map.

ADB is providing $2.2 million, financed on a grant basis by the ADB-administered Carbon Capture and Storage Fund under the Clean Energy Financing Partnership Facility. In 2009, the Global Carbon Capture and Storage Institute contributed to establish the fund. In April 2012, the United Kingdom announced financing for CCS development in developing and emerging countries.

## Public opinion divided in Saskatchewan

www.ipac-co2.com

**Saskatchewan residents have strong but divided opinions about climate change and CCS technology, concluded a public opinion survey commissioned by IPAC-CO2 Research Inc.**

"Almost seven in ten (68%) residents are concerned about climate change," said Joe Ralko, Director of Communications for IPAC-CO2, who managed the survey.

"However, there is no consensus on how to address the problem. That could be because the survey discovered there is no agreement on what residents believe to be the main sources of greenhouse gas emissions. What the people of Saskatchewan are saying is that whatever steps are taken to mitigate climate change must be effective."

Saskatchewan residents are clear on their trusted sources of information on climate change.

"Our study shows scientists and researchers (73 %) are the most trusted source for information but they are confused about the impacts of CO2 on the environment, and don't know what the risks and benefits of carbon capture and storage are," said Dr. Carmen Dybwad, Chief Executive Officer of IPAC-CO2.

"People are overwhelmed by the information that is out there, which is why there needs to be a group like IPAC-CO2 who can communicate about CCS and climate change."

Responses for the survey were collected from 1,003 Saskatchewan residents between May 30 and June 8 using Insightrix Research Inc.'s proprietary online panel, SaskWatch Research™.

"We set specific quotas for demographic variables, such as: age, gender, education, region, income and voting, to ensure the sample of respondents mirrored the general population throughout Saskatchewan," said Briana Brownell, Manager of Analytics at Insightrix.

Thirty-two percent of those surveyed believe that CCS could be very or fairly effective in fighting climate change while 39 percent think it would not be very effective, or not at all effective.

The remaining 29 percent are unsure, which is a notable increase from the 2011 research where 20 percent of those surveyed did not have an opinion whether or not CCS would be effective in fighting climate change.

A majority of Saskatchewan residents (58%) believe that climate change is occurring due to a combination of human activity and natural climate variation. Some (21%) believe that climate change is occurring due to human activity, and even less think that climate change is occurring only because of natural variation (16%).

"Compared to 2011, the opinions of Saskatchewan residents on their anticipated level of concern if a carbon dioxide (CO2) storage site was to be located within 5 kilometers of their home has shifted," said Brownell.

"The proportion who would be fairly or very worried has decreased (from 49% to 43%), while a higher proportion of residents are unsure (10% vs. 16%)."

A national survey on Public Awareness and Acceptance of CCS in Canada will be released by IPAC-CO2 in August 2012.

## UK Don Valley project leads EU funding bid

www.2coenergy.com

**The European Commission has announced that 2Co Energy's Don Valley CCS Project currently leads the EU's funding contest.**

2Co's 650MW Don Valley project in South Yorkshire, UK now leads a list of European CCS projects competing for a share of an estimated €1.3 to €1.5billion funding pot.

The NER300 funding programme is one of the world´s largest funding programmes for low carbon energy commercial demonstration projects and a key component of the EU´s strategy to tackle climate change. It also is one of the EU´s major policy initiatives to stimulate growth and employment across the EU.

The Don Valley CCS Project has already won €180m in European funding making it one of the most advanced CCS projects in Europe. Recently, Samsung C&T and BOC each agreed to take an equity stake in the Project.

# Diamond X-Ray imaging used to evaluate capture efficiency

Scientists from the University of Leeds are using the UK's national synchrotron to investigate the efficiency of calcium oxide (CaO) based materials as carbon dioxide sorbents.

CaO based materials have a large range of applications including pre- and post-combustion carbon capture technologies and thermochemical fuel upgrading. They are low cost, high abundance, have a large sorption capacity and fast reaction rates during the chemical process. They capture CO2 in the temperature range 400-800 °C via the formation of calcium carbonate (CaCO3) which can be regenerated with subsequent release of CO2, ready for compression and storage.

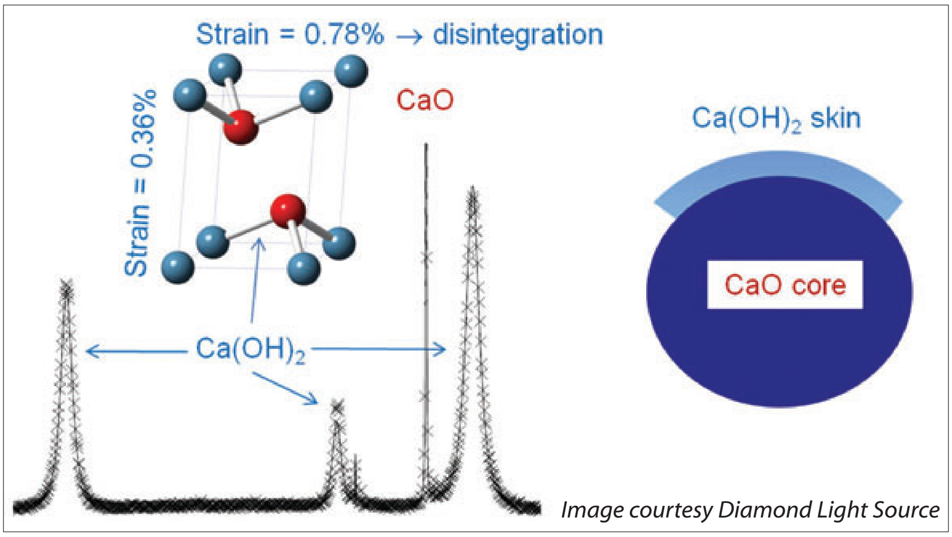
However, after multiple capture and regeneration cycles, the materials' capacity for capture decreases due to the loss of surface area through sintering, a process that fuses powders together to create a single solid object. Although the surface area can be restored through hydration, the material suffers a reduction in mechanical strength. If these problems can be overcome, CaO based materials could provide a low cost answer for carbon capture on a very large scale.

"In-situ X-ray diffraction of CaO based CO2 sorbents" was published in the Journal of Energy & Environmental Science. The results provide an explanation for one of the key mechanisms involved in CaO based capture. This new knowledge will inform efforts to improve the efficiency of this economically viable method of carbon capture and storage.

Led by Dr Valerie Dupont and Dr Tim Comyn from the University of Leeds' Faculty of Engineering, the team carried out a series of experiments on Diamond's High resolution powder diffraction beamline, I11, using intense X-rays to study the carbon capture and hydration process in CaO based materials on the nano-scale. Their observations suggest a mechanism for the interaction between CaO and water during hydration.

"We found that the stresses in the calcium hydroxide phase when bound to CaO were more than 20 times higher than its strength, leading to disintegration and the generation of nano-sized crystallites," explained Dr Comyn.

"Although the generation of a high surface area is a good thing, mechanical friability needs to be kept in check in order to achieve long term reliability for these systems. Our analysis provides an explanation of the enhanced capture/disintegration observed in CaO in the presence of steam. Now we understand this, the next step is to develop methods for improving the materials used, and apply the same techniques to other systems."




*CaO readily forms a shell of calcium hydroxide when exposed to water in the air (right). Due to differences in atomic congurations (top left) between the oxide and hydroxides, enormous strains develop due to the interface. These strains of 0.78% lead to stresses 20 times higher than the rupture strength of the hydroxide leading to rupture and the generation of nanoparticles.*

*Deconvolution of the data generated by Diamond (bottom left) allows the Leeds team to determine the size and strain in these layers, from the breadth of the peaks (the peaks from CaOH are far narrower than CaO). Conventional X-ray sources would have considerable peak overlap, making this type of analysis almost impossible*

Roger Molinder, an Engineering and Physical Sciences Research Council (EPSRC) funded PhD student on the project, describes, "Using the high resolution powder diffraction beamline at the Diamond synchrotron was key to this discovery; conventional X-ray sources such as those found at most Universities in the UK provide data with broad peaks, which do not make this sort of analysis possible."

"From a rigorous analysis of peak shapes arising from the data, we were able to determine the shape and size of the hydroxide phase, and determine the level of stress. Knowledge of these derived parameters is key to understanding the mechanism of sintering/disintegration."

CaO based materials are a promising candidate for the removal of CO2 from flue gases at temperatures between 400 and 800 °C from processes such as fossil-fuel combustion. They are also being considered as a means to remove the CO2 that is generated as a result of thermochemical fuel upgrading with biomass sources, which are growing more and more popular as an alternative to fossil fuels. Using CaO based materials for carbon capture is just one of the ways to combat global warming.

Since CaO based materials are low cost, there is an economic incentive to solve the problem of surface area loss to potentially turn this into a method for large scale CO2 capture. These recently published results are a promising step towards improving these low cost methods.

## More information

www.leeds.ac.uk
www.diamond.ac.uk
pubs.rsc.org

# Corrosion in amine systems - a review

Irrespective of consistent and dominant usage of aqueous amine based processes in acid gas capture facilities since the 1930s, there is constant concern over a number of operational snags including, but not limited to, corrosion.

**By Muhammad Hasib-ur-Rahman, Faïçal Larachi, Department of Chemical Engineering, Laval University, Quebec, Canada**

Various physical/chemical factors like process temperature, amine type/concentration, metallurgy, CO2 concentration, other gaseous impurities, gas loading, suspended particles, and heat stable salts, play their respective role in intensifying the corrosion occurrence that also favours solvent degradation. This obligates the use of additives that not only supplement the cost but also pose a risk to the environment, as typically heavy metals such as arsenic, vanadium etc. constitute the more efficient corrosion inhibitors.

## What else then?

Replacing water with more stable room-temperature ionic liquid (RTIL) in amine based systems might be an optimistically workable option as it renders three benefits: excellent corrosion control, stoichiometric maximum gas loading by overcoming equilibrium limitations through carbamate precipitation, and separation of CO2-captured product in the form of carbamates.

This strategy might also promise additive-free capture fluids. Moreover, easy separation of solid carbamate can offer cost-effective regeneration. As comprehensive scrutiny is still needed in this regard, the limited work has shown some good prospects of alkanolamine/RTIL mixtures as more optimal successors of aqueous amines for CO2 capture.

## Perspective

Amine-based chemical solvents have been in practice for over half a century in the oil and gas processing industry and are being considered as one of the best potential candidates for CO2 capture from flue gases. However, this cannot be a trouble-free technology regarding post-combustion capture in particular as flue gases contain particulate matter as well as acid gas impurities other than CO2 (like H2S/SO2) that ought to be removed separately [1,2]. Besides, corrosion of equipment and amine degradation further adds to process downsides.

All aqueous amine-based CO2 capture installations are susceptible to corrosion that not only adds to process costs but also raises concerns about the safety of personnel and environment. A number of factors like higher CO2 loading, increased amine concentration, elevated process temperature, as well as presence of oxygen greatly intensifies the corrosion of metal (Figure 1). Moreover, presence of suspended solid particles and amine degradation products/heat stable salts also causes augmented corrosion phenomena. The process equipment typically vulnerable to corrosion includes absorber, amine exchanger, regenerator, and pumps [3,4].

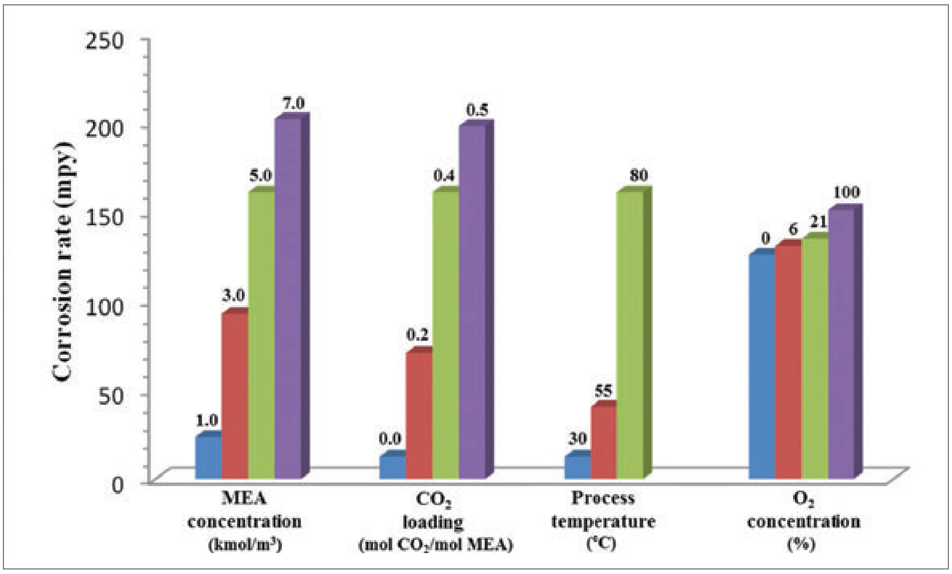



*Figure 1: Effect of various parameters on the corrosion rate of carbon steel C1020 in aqueous MEA (basal conditions: MEA conc. 5 kmol/$m^3$; gas loading 0.4 mol CO2/mol MEA; 80 °C temperature) [4]*

In aqueous alkanolamine-CO2 systems corrosion is the result of anodic (iron dissolution) and cathodic (reduction of oxidizers present in the solution) electrochemical reactions on metal surfaces. In CO2-loaded aqueous amines, iron dissolution is induced by various oxidizing species such as hydrogen/bicarbonate ions, protonated amine, carbamate ions, and undissociated water [4]. The most significant redox reactions arising in this regard, are:

$$Fe \leftrightarrow Fe^{2+} + 2e^-$$
$$2H^+ + 2e^- \leftrightarrow H_2$$
$$2HCO_3^- + 2e^- \leftrightarrow 2CO_3^{2-} + H_2$$
$$2H_2O + 2e^- \leftrightarrow 2OH^- + H_2$$

In case of either flue gas or raw natural gas, CO2 generally occurs in conjunction with some other acidic impurities like SO2, H2S that also help accelerate wear and tear of the metallic tools. For instance, the SO2 amount in flue gas is directly proportionate to iron dissolution through the formation of hydrogen ions as shown below [5]:

$$SO_2 + H_2O \leftrightarrow H^+ + HSO_3^-$$
$$HSO_3^- \leftrightarrow H^+ + SO_3^{2-}$$
$$SO_2 + ½O2 + H_2O \leftrightarrow 2H^+ + SO_4^{2-}$$

The H+ ions serve to abstract electrons from metallic iron resulting in oxidative decay of the equipment:

$$Fe + 2H^+ \leftrightarrow Fe^{2+} + H_2$$

Amine degradation products have also been found to increase the corrosion rate and corrosion products then lead to further amine degradation. Degradation occurrence not only depletes the active CO2 capturing material but the resulting species also speed up the corrosion rate by introducing additional oxidants. In fact corrosion and degradation phenomena are closely interrelated. For optimal functionality, perpetual removal of contaminants (degradation/corrosion products, particulate matter, etc.) from the chemical solvent is required [2,6,7].

## Corrosion control

Various approaches can be practiced to prevent corrosion to avoid severe operational problems in amine treating units. These may include process-specific equipment metallurgy/design, removal of contaminants, and use of corrosion inhibitors. The last option has been accomplished in industry quite effectively. A number of corrosion inhibitors, based on arsenic, antimony, vanadium, copper (like NaVO3, CuCO3) are being used in order to control and prevent corrosion that not only adds to the capital cost but most of these are toxic and hazardous to life as well. Stricter regulations in the case of toxic/hazardous substances in the very near future may limit the use of such compounds due to high disposal costs [8,9].

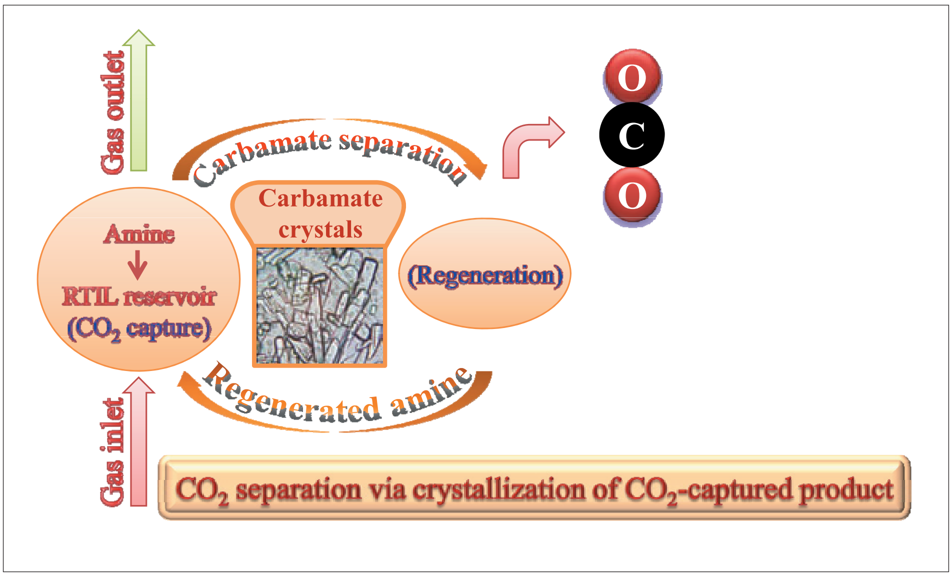



*Figure 2: Schematic concept of CO2 scrubbing by amine-RTIL blends*

## Alternative workable route

Replacing the problematic aqueous phase (chiefly responsible for corrosion occurrence) with some apposite solvent such as non-corrosive room-temperature ionic liquids under gas capture conditions might be a viable option at least as a near-term solution.

### Alkanolamine/room-temperature ionic liquid blends

Imidazolium based room-temperature ionic liquids (RTILs) are thermally stable, virtually non-volatile, and generally non-corrosive. RTILs being of tunable nature, because of the availability of manifold ion-pair combinations, can be tailored by choice in accordance with the individual process requirements and hence can be used as a replacement of water in alkanolamine based CO2 capture processes.

These can significantly suppress corrosion phenomena when combined with primary/secondary alkanolamines [10,11]. Moreover, such novel schemes also offer some momentous benefits regarding CO2 separation methodology [10-13]:

- Carbamate precipitation/crystallization
- Stoichiometric maximum gas loading by avoiding equilibrium limitations contrary to what is experienced in aqueous amine based systems
- Enabling easy separation of solid carbamate thus promising cost-effective regeneration

Larachi's research group at Laval University has studied the corrosion behaviour of carbon steel 1020 in alkanolamines blended with hydrophobic or hydrophilic ionic liquids [10,11]. Linear polarization resistance (LPR) measurements followed by Tafel extrapolation method was employed using a Bio-Logic VSP potentiostat. Diethanolamine (DEA)/hydrophobic 1-hexyl-3-methylimidazolium bis(trifluoromethylsulfonyl)imide ionic liquid ([HMIM][$Tf_2$N]) combination appeared to better control corrosion occurrence even at higher temperature.

The results showed that at 60 °C, even in the presence of oxygen and moisture along with CO2, the corrosion rate was negligibly small (<1 mpy) as shown in Figure 3.

To know the effect of ionic liquid's hydrophobic/hydrophilic nature, three hydrophilic RTILs (1-butyl-3-methylimidazolium tetrafluoroborate [BMIM][$BF_4$], 1-ethyl-3-methylimidazolium tetrafluoro borate [EMIM][$BF_4$], 1-ethyl-3-methylimidazolium trifluoromethanesulfonate [EMIM][Otf]) were studied in more detail.

Effects of amine/RTIL type, water content, CO2 loading, O2 concentration in simulated flue gas, water content, as well as temperature were evaluated. At 25°C, the amine/RTIL blends showed good corrosion control but at higher temperature (60°C) the carbon steel underwent a substantial amount of corrosion, however, it was still lower up to about 70% when compared to what was observed in aqueous monoethanolamine (Figure 4).

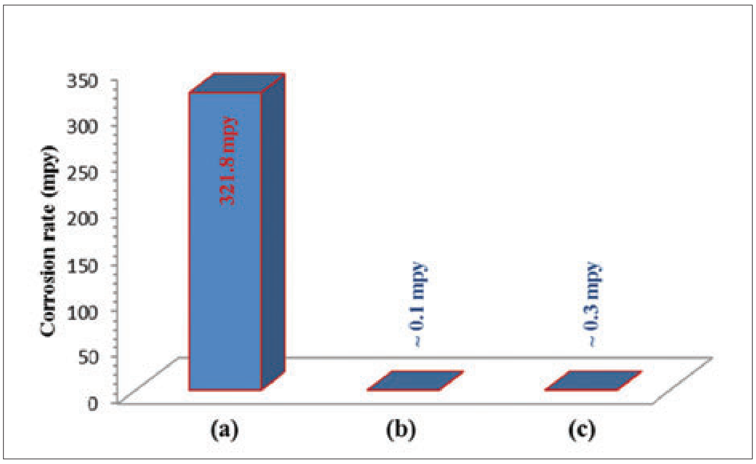



*Figure 3: Corrosion rate of steel 1020 under CO2+O2+H2O(vap.) atmosphere, a) Aqueous diethanolamine (15% w/w); b) Pure [HMIM][$Tf_2$N]; c) Diethanolamine/RTIL emulsion (15% w/w)*

Since the CO2-captured product (carbamate) moves away from the reaction phase as solid moieties, it is no longer involved in the electrochemical corrosion reactions. Also, RTIL coating on metal surface barricades the access of any oxidants to the working electrode facet. Furthermore, the absence of aqueous phase, that in combination with CO2/O2 provides the bulk share of oxidizing species in the case of aqueous amine solvents, diminishes the chances of the occurrence of redox process.

The results also demonstrated that hydrophobic ionic liquids, compared to hydrophilic ones, could efficiently prevent metal deterioration at higher temperatures and might offer more success if the whole bulk of gas capturing amine/RTIL fluid would be subjected to thermal regeneration. This supremacy is probably due to its superior safeguarding through coating/adsorption on the metal surface and also because of its repelling behaviour towards water species.

In spite of the above cited outcomes, prior to large scale applications, a significant amount of work is still required to exactly evaluate the corrosion phenomenon under real regeneration conditions. Moreover, it is yet to be scrutinized if we can avoid amine degradation by using this stratagem, and the impact of impurities / contaminants also needs appraisal.

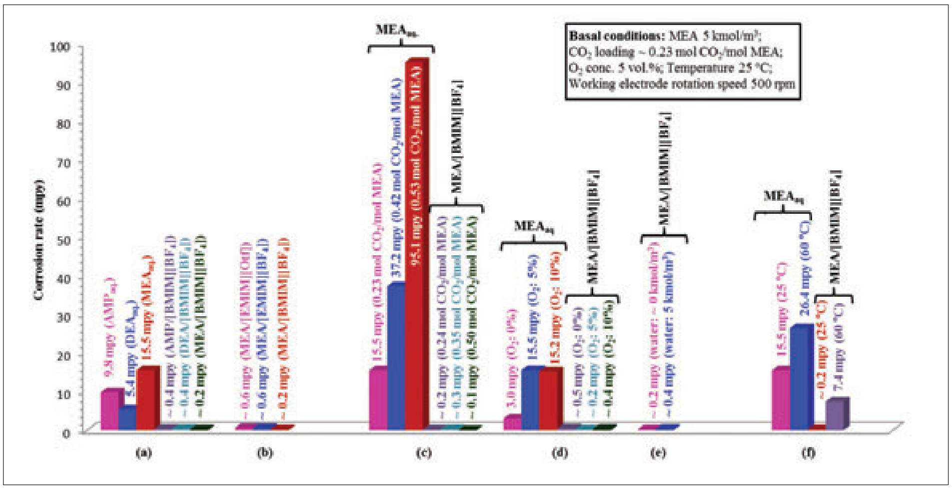


*Figure 4: Various process conditions tested for amine/RTIL (hydrophilic) blends, a) Amine type; b) RTIL type; c) CO2 loading; d) O2 conc. in flue gas; e) Water content in the fluid; f) Temperature effect*

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### More information

**Muhammad Hasib-ur-Rahman** holds an M.Phil. degree in Inorganic/Analytical Chemistry from Quaid-i-Azam University (Islamabad, PAKISTAN). Currently he is a PhD student in Chemical Engineering Department, Laval University (Quebec City, Canada) working on application of blended amine/ionic liquid systems for CO2 capture.

**Faïçal Larachi** is full professor of Chemical Engineering and the holder of a tier one Canada Research Chair "Process intensification for cleaner and sustainable energy and materials". He holds a doctoral degree from the Institut National Polytechnique de Lorraine in France. His research interests encompass multiphase reactor engineering, chemical kinetics, process intensification, and new approaches for mitigation of greenhouse gas effect via mineral carbonation, ionic liquids and enzymatic catalysis.

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# Capture news

## Closing in on a solution for amine emissions

www.statoil.com

**Statoil says it has made good progress in solving the challenges associated with amine emissions from carbon capture at Mongstad.**

Through the full-scale CO2 capture project at Mongstad (CCM), Statoil and Gassnova have developed a set of methods for conducting adequate risk assessment as regards emissions from amine technologies. This will make it possible to test whether emissions from amine technologies will be under the limit values set by the Norwegian Climate and Pollution Agency (Klif).

"We are very pleased that we have developed a toolbox that enables us to analyse emissions from open amine facilities for capture of CO2, including assessing the degree to which humans and the environment are exposed to hazardous components from such facilities," says Arne Myhrvold, head of HSE in Statoil's CCM project.

The work on the toolbox has been an important part of the CCM technology qualification process, which started in the autumn of 2011.

The toolbox includes sampling, treatment and analysis of emissions from amine facilities to both air and water. The methods include extensive variables linked to formation, degradation and spread in the atmosphere, as well as exposure to potential hazardous substances from amine emissions.

“Until now, the methods for calculating these emissions have not been good enough, and this has been one of the most significant uncertainty factors in relation to health risk linked with amine-based CO2 capture facilities. The methods developed through this work is a confirmation that the decision to carry out a technology qualification process was sensible,” says Myhrvold.

Extensive research activity initiated and carried out by Statoil, Gassnova and their partners has considerably enhanced knowledge about emissions from amine facilities.

“Now we have the methods that enable us to measure these emissions, and the resulting exposure. Together with Klif’s emission limits, we have what we need to test various amine technologies in a manner that is prudent and comparable,” says Myhrvold.

Statoil and Gassnova started a technology qualification programme for CCM in the autumn of 2011. The programme is now entering a phase in which technologies supplied by Mitsubishi Heavy Industries LTD, ALSTOM Carbon Capture GmbH, Siemens AG, Aker Clean Carbon and Huaneng-Ceri Powerspan Joint Venture will be tested in separate test facilities.

“The CCM project will now start extensive testing of various technologies to investigate whether they are able to comply with the emission criteria set by Klif,” says Myrvold.

Statoil and Gassnova have cooperated with a number of leading international research institutions to develop this toolbox, including NILU, NIVA, Yale, Sintef, TEL-TEK, the University of Oslo, DNV, CERC, CSIRO Rambøll and the University of Illinois.

“We want to share these methods with others, and our goal is for them to become the industry standard for open amine facilities. The work we have done through the CCM project has been pioneering, and the results are a very important milestone; not just for the CCM project at Mongstad, but for the entire industry in its work to develop CO2 capture technology”, says Myhrvold.

## Codexis releases enzyme CO2 capture results

www.codexis.com

**Codexis has unveiled preliminary results from its pilot scale demonstration at the U.S. National Carbon Capture Center (NCCC) in Wilsonville, Alabama.**

The field test, on flue gas emitted from a Southern Company's power plant, shows that enzymes have promise to facilitate CO2 capture at coal-fired power plants, said Codexis.

This is the largest scale that enzyme-based carbon capture technology has been demonstrated to date, with the equivalent daily capture rate of 1,800 average sized trees per day.

## Akermin pilots capture system with Southern Company

www.akermin.com

**Akermin has signed an agreement with Southern Company Services to install and operate a pilot plant incorporating its biocatalyst delivery system at the National Carbon Capture Center.**

As part of a two-year project, partially funded through a grant from the US Department of Energy, Akermin is designing a pilot plant to demonstrate the performance of its enzyme based biocatalyst system for high efficiency carbon dioxide capture.

The project is on schedule to be commissioned in the 4th quarter of 2012 and will allow Akermin to demonstrate sustained biocatalyst performance over an extended period when capturing carbon dioxide from the flue gas of a coal-fired power plant. Akermin intends to operate the pilot plant for up to six months. During this period, it will collect data to validate system performance, including biocatalyst performance, energy consumption, carbon dioxide removal efficiency, capture of residual SOx and NOx emissions, by-product quality for potential resale and other parameters.

"This project signifies Akermin's transition from laboratory testing and development to field pilot testing and demonstration marking a key step towards commercialization of our technology," said Barry Blackwell, Akermin President & CEO.

"The results from this pilot project will help to prove the viability of our technology to capture carbon dioxide from industrial processes and accelerate development of commercial partnerships and future demonstration projects covering multiple market applications."

Akermin's biocatalyst delivery system incorporates the use of an enzyme that is being supplied by Novozymes, a leading enzyme supplier, based in Denmark. The pilot plant is sized to capture over 90% of incoming carbon dioxide.

Akermin's current prototype has been operated on a continuous basis for several months in a bench-scale system that captures carbon dioxide from synthetic gas and has demonstrated excellent performance. In recent weeks, this system was relocated to operate on a coal-fired boiler capturing carbon dioxide from actual flue gas containing SOx, NOx, mercury, particulates and other impurities. In these tests, the system demonstrated continuous capture of over 90% of incoming carbon dioxide over a period of three weeks. During this period, there was no observable decline in biocatalyst activity.

## New material for CO2 absorption

cordis.europa.eu

**A team of researchers, led by the University of Nottingham (UK), has developed a novel porous material that has unique carbon dioxide retention properties.**

The chief feature of this new material is its absorption of CO2, which the researchers say could have an impact on the development of new carbon capture products designed to reduce emissions from fossil fuel processes. The team's results have been published in the journal Nature Materials.

"The unique defect structure that this new material shows can be correlated directly to its gas absorption properties," said the head of the research team, Professor Martin Schröder from the University of Nottingham.

"Detailed analyses via structure determination and computational modelling have been critical in determining and rationalising the structure and function of this material."

The interlocked metal organic framework the researchers created is called NOTT-202a. It consists of tetra-carboxylate ligands, a structure made up of a series of molecules or ions bound to a central metal atom filled with indium metal centres. The structure resembles a beehive, as it is arranged in a honeycomb-like pattern, allowing CO2 to be absorbed selectively. While other gases, such as nitrogen, methane and hydrogen, can pass through the structure, CO2 remains trapped in the material's nanopores, even at low temperatures.

The team used x-ray powder diffraction measurements to gain insight into the unique CO2 capturing properties of the material, as well as computer modelling to probe the material at the Diamond Light Source UK research facility.

The study was funded in part by the COORDSPACE ('Chemistry of coordination space: extraction, storage, activation and catalysis') project, which received a European Research Council (ERC) grant worth EUR 2.5 million under the EU's Seventh Framework Programme (FP7).