



CALIX CARBON CAPTURE (“3C”)

TECHNICAL SUMMARY

Background

The environmental impact of anthropogenic carbon dioxide emissions, which are currently at about 23.4 Gt², is now recognised to be the major risk to mankind. Reducing these emissions will be the greatest industrial challenge of the 21st century.

Carbon Capture and Sequestration (CCS) processes aim to reduce CO₂ emissions by capturing CO₂ from industrial processes (power, cement, steel) that burn fossil fuels, and sequestering the CO₂ in deep saline aquifers, depleted oil/gas fields, deep coal seams, or deep ocean reservoirs.

The size of the CCS market is immense (Attachment 1), being well in excess of US\$100 billion by 2025. This is so quickly developing that the business process of achieving its adoption will not fit a classical model³ of a single source. Introduction into the market will be greatly assisted by carbon credits and/or taxes in different regions⁴. National security would be a significant benefit from a successful CCS implementation, because coal reserves are large, well established and relatively secure. It may be preferable to nuclear power. In addition, coal and gas exporting countries such as Australia will benefit greatly if CCS is successful, and CCS is a strategic technology for ensuring that these export markets will be maintained. Thus CCS is an essential technology for the development of a “Clean Coal” market. It is also important for the steel, cement and chemical industries, as they are forced to reduce CO₂ emissions (Attachment 1).

There are three approaches to carbon capture for the CCS application – post-combustion capture, pre-combustion capture and oxy-fuel combustion. Pre-combustion capture would be used, for example, in an Integrated Gasification Combined Cycle power plant. However, the initial capital costs of a power plant based on this approach are believed to be very high, and more development work is required. Oxy-fuel combustion uses oxygen instead of air, but suffers from the very high cost of separating oxygen from air, and may never be commercially viable. Post-combustion capture is believed to be the most promising CCS process, with the benefit of being more easily integrated into existing power generation systems. The C3 process described below is a post-combustion process.

Expert reports, such as “*The Prospects for Carbon Capture and Storage*” from the International Energy Agency (IEA), consider a number of strategies to reduce emissions using CCS. The IEA report and others have fed into the report from the UN’s Intergovernmental Panel on Climate Change 2005 (IPCC) on CCS. Roadmaps for CCS have also been published^{5, 6}, including one by the research organisation, CO2CRC, in Australia⁷. All the scenarios presented by the IPCC see

² Gt = Gigatonnes per annum = 10⁹ tonnes pa

³ If the total “market” for CCS is ~10 Gt at US\$10 per tonne, giving US\$100 billion in the long term. The initial market will be higher and will be supported by carbon credit and carbon tax initiatives.

⁴ It has been announced (SMH Aug 2, 2006) that California will join the EU Carbon trading market. This splintering of the US objection to this model will ultimately impact in Australia. Calix will operate in those countries where such incentive systems can promote its early adoption.

⁵ C. Henderson, “Clean Coal Technology Roadmaps”, Report of CCC/75, IEA Clean Coal Centre, London, UK 2003

⁶ McKee, “Carbon Sequestration Leadership Forum. Final draft technology roadmap” www.cslforum.org (2004)

⁷ “Carbon Dioxide Capture and Storage Research and Demonstration in Australia: A technology roadmap” CO2CRC, Canberra, ACT, Australia (2004)



an increase of the CO₂ levels from today at 375ppm to between 600 and 950ppm, with significant global warming arising from these and past industrial emissions. The widespread adoption of a successful CCS technology by 2025 will stabilise the CO₂ levels at about 600ppm by 2050. The first power plants using CCS would be deployed in about 2015.

The International Energy Agency (IEA) reports that energy demand is expected to rise by 60% up to 2030, with over 70% of the increase coming from developing countries, such that by 2030, these economies will be responsible for over 49% of all emissions. If CCS is widely deployed by 2025 on all new systems, then power plants with CO₂ capture would represent 22% of the total global installed generation capacity and produce 39% of all electricity in the longer term. Capture from coal fired process would represent 65% of the total CO₂ captured from power plants, with the remainder coming from gas, oil-and biomass-fired processes, and from cement kilns (Attachment 1).

The potential for CCS in 2050 is estimated to be 5.5-19.2 Gt, and almost half the capture activity would be in developing countries such as India and China.

The transport, sequestration and monitoring of CCS are both well established, and their costs are not a hurdle to the adoption of CCS. However, there is currently no established carbon capture process that has been shown to be economically viable for CCS. Thus the focus of attention for CCS is on the techno-economics of carbon capture technologies.

Only one carbon capture process is commercially used, but not for a CCS application. This process, called the MEA process, uses monoethylamine and similar compounds, and is currently used by the petroleum industry to separate CO₂ from natural gas, where the CO₂ has been injected into the reservoir to force out the hydrocarbons. The MEA process separates the natural gas from the CO₂, and regenerates the MEA sorbent for a cyclic process. MEA uses amines (and similar materials) as the sorbent, and the reverse process uses steam to release the CO₂ to regenerate the amine. The MEA process could operate today as a post combustion process in a power plant at a cost of US\$50-70 per tonne of CO₂ avoided, well in excess of the target of US\$10-20 per tonne of CO₂ avoided, as required for the CCS application⁸. MEA technology will not be used in its present form because it consumes too much energy from the power plant. Calix understands that the energy industry is sceptical that the costs of the MEA process can be reduced to meet the target for being economically viable in the CCS application. MEA is a toxic material, and its use best avoided.

Thus there is a world-wide effort to develop new carbon capture technologies that can meet the long term cost target for CCS. These developments include physical adsorption processes (so called "pressure swing") such as adsorption on membrane materials, and new chemical sorbents (so called "temperature swing"). The C3 process is a dry chemical sorbent process for post-combustion CCS that uses a non-toxic, plentiful, low cost material.

In general, there is a growing concern in governments across the world that none of the existing and new technologies for CCS may be demonstrated as being economically feasible over the next 5 years. One consequence is that many countries are now reassessing the nuclear power option. The IEA contends that there is a 5 year window of opportunity for the introduction of a new CCS technology to enable it to be deployed in demonstration power plants by 2015, with widespread deployment by 2025. Calix intends, through this business plan, to bring its C3

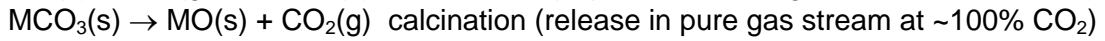
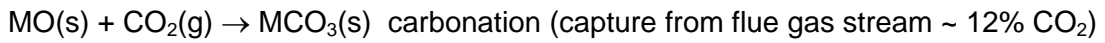
⁸ There are two costs that have to be calculated in an assessment of a carbon capture technology. The first is the cost of carbon capture itself, and the second is the cost of CO₂ avoided. The latter takes into account the fact that a carbon capture technology consumes energy, and the energy from combustion that is available to produce electrical energy is reduced. Comparisons between technologies are made on the basis of the cost of CO₂ avoided.



technology to market within the 5 year timeframe.

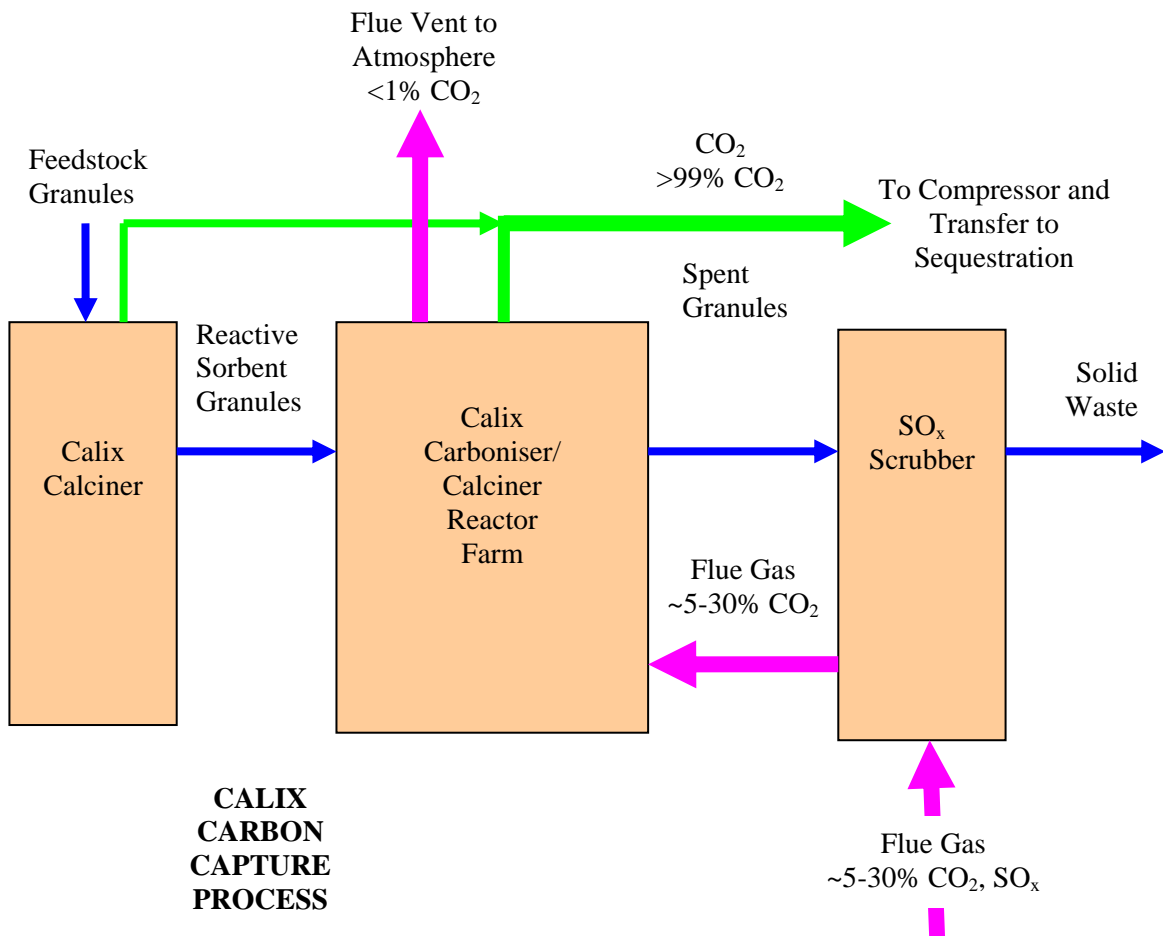
The C3 Technology

Calix Carbon Capture (“C3”) is a regenerable, dry sorbent temperature-swing process based on the metal oxide carbonation/calcination cycle. In this process, CO₂ is captured from the flue gas stream by the reaction of granules of the metal oxide (MO) with CO₂ in a carbonator reactor at a low temperature to form the carbonate MCO₃, and then releasing the CO₂ by heating the carbonate in a calciner reactor to generate a pure CO₂ gas stream which is compressed for transport and sequestration, and to regenerate the oxide granules. The granules are reinjected into the carboniser, to establish a continuous cycle. The chemical reactions are:-



This concept of using the carbonation/calcination cycle was first proposed in 1999 for calcium (M=Ca).

The C3 process is shown in the diagram below:-





An EU consortium has been recently formed to fund and develop this technology for CCS⁹. The EU project aims to establish a 1 MWth pilot plant. The IEA has singled out this process¹⁰ for mention in its report, but commented that the conditions under which the reactivity of CaO was maintained had not yet been found. Calix understands that industry is sceptical about the economic feasibility of this process based on calcium because the reaction is too slow, with the consequence that the footprint of the infrastructure is too large to be integrated into a power plant. The Calix C3 process will eliminate these two hurdles by maintaining reactivity and reducing the footprint.

The C3 process has been simulated in heat and mass transfer calculations using as inputs the known thermodynamics of the materials and the kinetics of the chemical reactions. The C3 process is protected by a number of provisional patents, and considerable know how. A US patent has recently been granted to the inventors involved in the EU project described previously. Their patent does not teach the core technology underpinning the C3 process.

Benefits of the C3 Process

The C3 process will reduce the cost of carbon capture in five ways:-

- The C3 process can use either the calcium cycle (M=Ca) or, potentially, the magnesium cycle (M=Mg). The calcium cycle has the benefit of using limestone¹¹ as a feedstock. Limestone is already used as a sorbent to remove sulphur emissions (SO_x) from burning fossil fuels in power stations. The net additional cost of feedstock for the C3 process is reduced to zero if the lifetime of the granule is sufficiently long that the throughput of the granules can be matched to the rate at which such granules are consumed by scrubbing the SO_x from the flue gases, to produce gypsum as a solid waste by-product. This depends on the S/C ratio in the flue gas. Then the C3 process simply makes intermediate use of the limestone already used in power plants. The calcium cycle operates at temperatures of ~550°C for carbonation and ~900°C for calcination. The magnesium cycle uses dolomite as a feedstock, and its advantage is that it is more easily integrated into a conventional steam fired power plant because it operates at ~300°C for carbonation and ~450°C for calcination, as well as being used to remove SO_x. Dolomite is not as plentiful as limestone as a feedstock, but is nonetheless an abundant mineral. In summary, the Calix C3 process uses feedstock which is abundant, and available at low cost, and potentially at no net additional cost.
- The C3 process uses a highly reactive oxide granule for injection into the carbonation/calcination cyclic reactors. These granules are made using the Calix Calcination process, which produces highly reactive oxide materials, and which is readily integrated into the CCS process. These granules have a very high surface area, so that the carbonation and calcination reactions are very fast. The size of the carbonation/calcination reactor scales with the residence time of the granules in the reactor, and Calix believes that its highly reactive oxides provide a key to adoption, by

⁹ The EU 6th Framework C3 Capture Project: "Calcium Cycle for Efficient and Low Cost CO₂ Capture in Fluidized Bed Systems". This project aims to develop a 1 MWth Pilot Plant. It commenced in Sept 2006. Industry members of the consortium include Alstom Power Boilers (France) and Cemex (Switzerland). The majority of the consortium members are university and government research laboratories from Germany, Russia, Spain, France, and Poland.

¹⁰ In 2005, the *International Energy Authority* in its definitive report "Prospects for CO₂ Capture and Storage (2005)" singled out the calcium calcination/carbonation approach a possible "new technology" for carbon capture

¹¹ Limestone is the fifth most common mineral on earth, and is part of the geological process that converts atmospheric CO₂ to minerals over millions of years. In this natural cycle, limestone is formed after 6,000 years in the seas, and then further reacts with silicates and aluminates. Limestone is not toxic, and is one of the cheapest minerals on earth.



lowering the reaction time to accommodate a low residence time. By comparison with other sorbents, the efficiency of CO₂ capture on a mass basis far exceeds other materials, even if the sorption efficiency is set at ~30% per pass.

- The C3 process uses a reactor design which is well established in the petroleum industry for the catalytic cracking of petroleum. The C3 process uses a Riser reactor for the slow carbonation reaction, and a Downer reactor for the fast calcination reaction. This is a very low cost system. The key is that the residence time of the granule in the calciner reactor is very short, ~ 1.5 sec, and the highly reactive granules calcine optimally within this time. This very short reaction time removes a major impediment to the adoption of the calcium technology that has been recently reported by the research group in the EU consortium, namely that the reactivity of the granules degrades during the high temperature calcination process. This degradation arises from sintering of the material, which closes the mesopores of granules such that the interior of the particle becomes increasingly inaccessible by CO₂ during the carbonation process. By using a very short reaction time, the C3 process reduces the accumulative degradation, simply because sintering of the particles is suppressed.
- The C3 process is scalable because the design is best suited to reactor module units. A reactor farm can be installed, operated and maintained in an effective manner, with the flue gases being routed through a number of modules, each operating optimally, so that the CO₂ fraction is progressively reduced. The short residence time of the gas and solids in the calciner reduces the volume of the calciner relative to other reactor designs, and this in turn reduces the footprint of a reactor module. The current design of the module is such that sufficient modules to remove the CO₂ from a 1,000 MW power plant could occupy a footprint of less than 1,500 m².
- The modular approach of C3 will enable small portable installations to be developed. This may open up new markets where there is an industrial market for CO₂, or where smaller companies can benefit from carbon trading systems. Such systems could be used in emerging economies where the cost of large power plants using large scale CCS cannot be met. The retrofit market is of considerable interest in its own right.

THE C3 PROJECT

The funding of the C3 project will be developed during the next 18 months as the basic parameters are determined. Commercialisation will involve application for very significant government grants, because CCS has been recognised as a critical project for Australia. Only CCS can create the Clean Coal scenario essential to Australia maintaining its coal exports, which today account for ~40% of all exports. Commercialisation will involve development of linkages to end users – the coal and power industries, and the systems integrator companies that provide the infrastructure for power plants and other industrial processes. It will take time to develop those linkages.

The pre-project costs of establishing the C3 project will be funded by the Calix seed capital. These activities include:-

1. Undertaking a techno-economic modelling of the C3 process using an independent third party to estimate the cost of carbon captured and avoided using the best estimates of the C3 process at the time. The objective of this work is to provide early guidance as to the key parameters that would enable C3 to meet the CCS cost objectives. This would use a model for a generic 1,000 MW plant, which has been adopted worldwide for comparisons



between different CCS technologies. This will allow a direct comparison with other approaches. A positive report would position Calix to take the leadership in the subsequent commercialisation.

2. To protect the core Intellectual Property through the development and submission of full patent specifications based on the C3 process.
3. To design and cost a module of the carboniser/calciner reactor as the basis for the C3 project, and to refine the techno-economic modelling. This outcome means that the C3 project can be kick-started with all the design, costs and techno-economic modelling completed. The experience gained in the Calix Calciner project will directly feed into the C3 reactor design.
4. To develop a number of strategic relationships with third parties that would include fossil fuel suppliers, power generators, systems providers to the energy industry and manufacturers, and with governments to resource the C3 project. This may include international groups. The availability of the techno-economic modelling would greatly assist this engagement.

MGS 2 August 2006



ATTACHMENT 1: BACKGROUND: COSTS AND MARKETS FOR CO₂ CAPTURE

Cost of CCS Technology

Today, the cost of carbon capture varies from US\$78 per tonne for coal fired plants to US\$115 per tonne for gas fired plants (due to their different CO₂ v/v% compositions in the flue gas). Analysis performed by SFA Pacific, Inc. indicates that adding existing technologies for CO₂ capture to an electricity generation process could increase the cost of electricity by 2.5 cents to 4 cents/kWh depending on the type of process. Thus it is not economically feasible to introduce CCS on a large scale at this time. CCS is currently only feasible where there is a market for CO₂. There is a limited market for enhanced oil recovery that is prepared to pay these costs.

It is anticipated that the costs of CCS will fall to US\$25-50 over the next 25 years. The most recent costing for capturing and storage of CO₂ range from US\$50-100 per tonne¹², and the future targets are to reduce this to US\$25-50 until 2030, “but this will require more efforts in R&D”. The US DOE target is US\$10 per tonne captured.

Reports on carbon capture and sequestration estimate the future costs of capture at about US\$30-50 per tonne of CO₂ using proven technologies, in anticipation of reductions through R&D, US\$3 per tonne for transportation of the superfluid CO₂, and US\$1-3 per tonne for sequestration in deep saline aquifers. The costs of capture are therefore US\$25-45 per tonne. We adopt the lower bound of US\$20 for the target cost for any new capture process. At this level, it is below the current trading credits for emissions. The analysis, not yet completed, indicates that the operating and capital depreciation costs of the Calix C3 process are significantly less than this cost.

Market Size

The burning of coal is responsible for 40% of emissions today, oil for 31% and gas 29%. The generation of electricity, which uses a mix of these hydrocarbons, generates 29% of the total emissions. The Renewable CO₂ emissions can be segmented as follows (see the IEA report for a more complete breakdown) into the top three industry sectors in 1999.

	Coal	Gas	Oil	Bio	Lime	Total
Total Emissions (Gt)	9.08	4.89	10.21	5.22	0.77	30.13
Electricity Sector	6.14	1.69	0.91	0.28		9.00
Energy Sector	0.11	0.46	0.62			1.20
Industry Sector	2.75	2.69	8.65	4.73	0.77	19.57

For completeness, the CO₂ emissions from the calcination of limestone are included under “lime”.

In 1999, there was 1,000 GW of power produced by coal fired power plants, and these produced approximately 6.14 Gt of CO₂. It is projected that by 2030, there will be an additional 1,400 GW from new power plants installed, of which 400 GW will be for replacement plants. That is, by 2030, there will be 2,000 GW produced by coal fired plants, an increase of 100% producing ~12 Gt of CO₂. The replacement of existing plants provides an opportunity for investment in new technology.

¹² OECD Report: Prospects for CO₂ Capture and Storage (2005) International Energy Agency



Within these sectors, the top three CO₂ polluting industries are:

- The electricity industry that uses coal, gas and oil, amounting to 8.74 Gt.
- The steel industry that produces 1.48 Gt.
- The cement industry that produces 0.77 Gt.

These three industries are responsible for 10.99 Gt of CO₂ emissions, corresponding to 36.5% of all the anthropogenic emissions of CO₂.