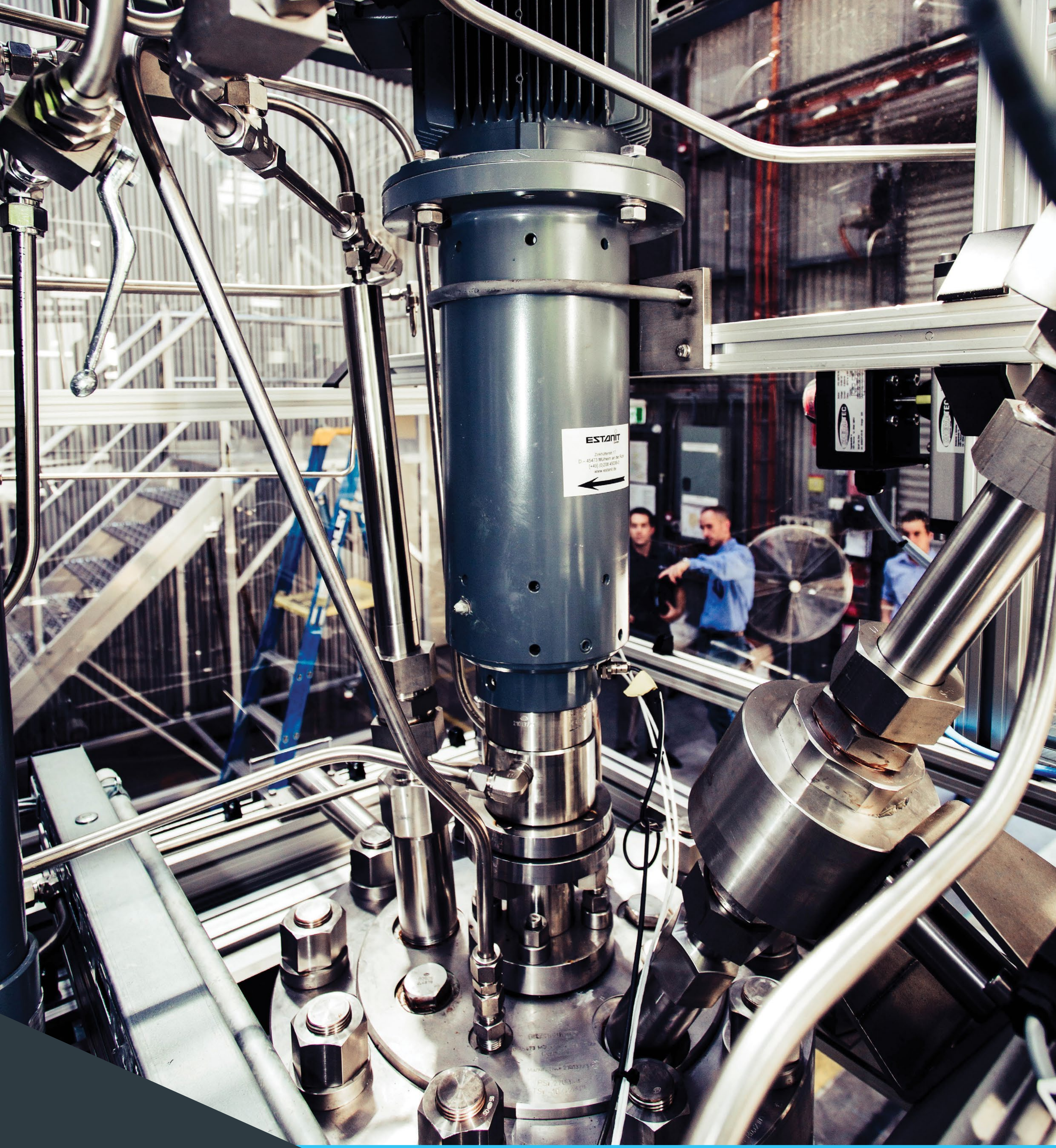


Turning captured CO_2 into valuable products for industry

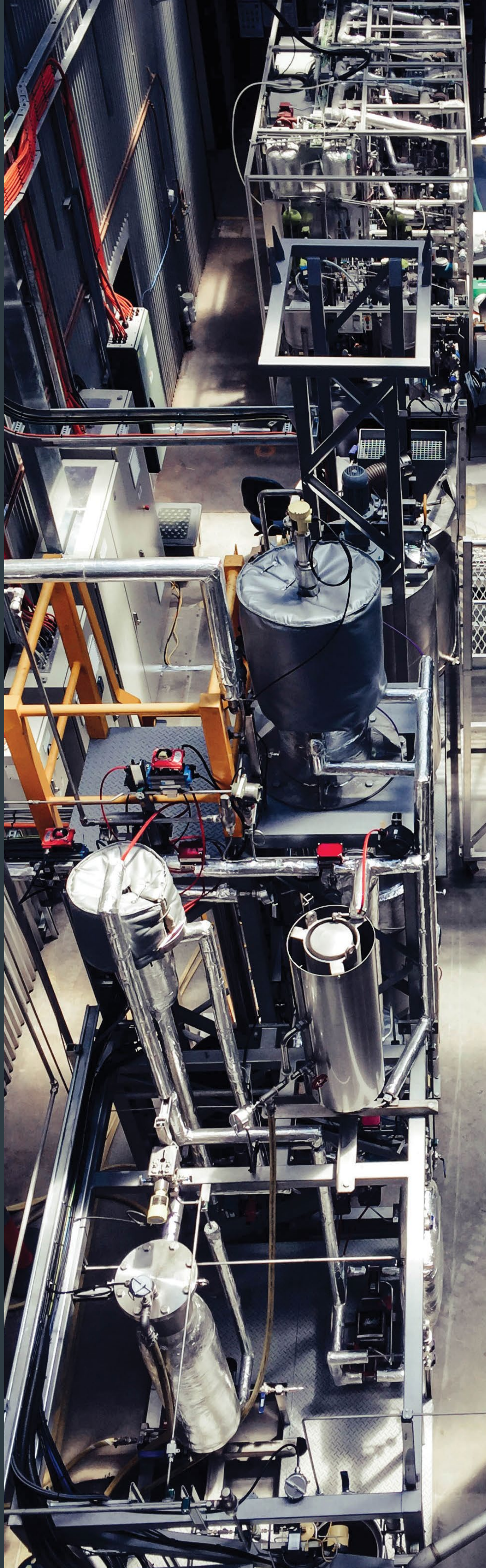
An Australian developed technology platform for CARBON UTILISATION

INITIAL FUNDED R&D PILOT PLANT PROGRAM FROM JULY 2013 TO JULY 2018

FINAL REPORT TO FUNDERS
COMMONWEALTH GOVERNMENT
COAL INNOVATION NSW
ORICA LTD

MAY 2019 (REDACTED) FOR POST PROJECT REVIEW UNDER NDA

Contents



Mineral Carbonation International has examined the feasibility of storing industrial CO_2 emissions by mineral carbonation and in doing so created a new process which could transform captured CO_2 into valuable products.

The MCi mineral carbonation process has the potential to offset the costs of CO_2 capture and storage. It may also result in profit through the sale of valuable products. More research and development is needed to confirm the feasibility of the new MCi process at industrial scale.

MCi's approach is carbon utilisation. If proven viable at industrial scale, the MCi process could make captured CO_2 a resource with economic value; so turning a problem into an opportunity. If feasible, carbon utilisation using the MCi process would play to Australian industry's major strengths in mining, bulk handling, materials processing and advanced manufacturing whilst also providing an export ready carbon management platform.

In December 2018, the MCi project completed its four and a half year research pilot plant program as described in this report. The project is a major R&D collaboration between a private industry consortium backed by Australian governments and industry, and local and international universities.

MCi will now seek to progress with further research and development, in particular in application of the MCi process to building material products, and to start commercialisation with industrial partners.

CO_2U (utilisation) can remove over 10% of the emitted CO_2 and represents an annual market opportunity of $0.8-1.1Trillion.

Source: Global Roadmap for Implementing CO_2 Utilization, CO_2 Sciences and The Global CO_2 Initiative, November 2016.

Statement from the CEO

Australia is a global resource superpower. Its economic prosperity has continually relied on its ability to develop domestic companies and industries around its key industrial and resource sectors and supply to global customers. Economists often cite the fact that Australia has had the longest continuous GDP growth of any country in the OECD. However, what got us here may not be enough to maintain our prosperity into the next decades if we do not continue to provide the innovation in new industries.

As the science of climate change predicts dire scenarios of environmental impact, we become more aware of the urgency to a ress this problem. Climate change and the transition of industries to low or zero carbon emissions is an economic, social, technological and political challenge for all countries. Clearly there is a need to have a range of technology solutions that can be developed, tested, scaled and applied in various industries that have large CO_2 emissions like cement, steel, chemicals and power generation.

MCi is a company that is founded on the challenge of developing a technology solution to economically turn CO_2 emissions into a bulk solid materials as a resource for industries like construction, advanced manufacturing, transport and infrastructure. Mineral carbonation converts the captured CO_2 gas into a solid. The process plays to Australia's strengths in mining, bulk materials handling and minerals processing.

Our initial 4.5 year MCi R&D program jointly funded by Australian governments and industry was conducted by leading researchers and engineers who set out to establish the feasibility of mineral carbonation as a large scale solution for industry to decarbonise. This report details the project and the major achievement of having moved the science from laboratory scale to a global reference pilot plant. We have also established the techno-economics of mineral carbonation to enable it to progress towards demonstration scale.

Following this program we are now proceeding with the initial commercialisation of MCi's technology involving capital raising and partnerships with industry in developing products from our outputs. Our Australian technology is well positioned to be a player in a potentially massive new industry sector by 2030 called "carbon utilisation" where CO_2 is turned into value-a ed products and is no longer considered just a costly waste to industry for disposal.

The scientific interest in mineral carbonation has accelerated globally with China, the USA and others now taking significant interest in the field. Our early mover advantage in this project has positioned us well with advanced understanding and IP development that should allow us to maintain our position as long as we can continue to fund our advances towards scaling to demonstration and industrial scale.

The collaboration framework developed in the MCi program between our funders, our researchers and our venture partners has been an essential element in our ability to deliver the outcomes detailed in this report. As CEO I commend this final report to our funders and stand proud in presenting an account of the tremendous human effort that has been put into the MCi program over 4.5 years by all the team members and participants.

Marcus Dawe
CEO Mineral Carbonation International
March 2019

MCi Project Executive Summary

Project Overview

Mineral carbonation is a carbon dioxide utilisation and storage technology that sequesters CO_2 by reacting it with naturally occurring magnesium silicate rocks, such as serpentinite, to form solid magnesium carbonate and silica. The carbonation reaction is exothermic (releases heat) and the carbonate product is stable on geological timescales, so there is no risk for leakage of CO_2 into the atmosphere. The process does occur naturally over millenia as a result of rock weathering. The goal of our research and development is to accelerate this reaction in an industrial setting with the output being utilised as valuable products making the overall process economically viable.

Mineral Carbonation International (MCi) was founded in 2013 as a joint venture between Orica, the University of Newcastle (UON) and Greenmag Group, with the aim of delivering a project to conduct research and to design, build and operate a pilot plant to assess the viability of mineral carbonation for CO_2 sequestration. The 4.5 year project was funded equally by Coal Innovation NSW, the Commonwealth Government and Orica with a total buțet of A$9.12M. At that time, the leading process was one developed by the ARC/NETL in the USA; a high pressure (150 bar) and high temperature (155 °C) aqueous single-stage process that required a pure stream of (captured) CO_2. MCi evaluated the ARC/NETL process and also began development of an alternative two-stage process that operated at lower pressure and temperature. Mineral carbonation has previously been considered too expensive as a carbon storage technology. However, with this global reference pilot plant, its techno-economic feasibility has been established.

The stated project outcomes before commencement were:

1. To decrease the cost of CO_2 storage by mineral carbonation
2. To decrease the energy intensity
3. To develop and test new and improved unit operations
4. To identify the production of offsets (by-products)
5. To identify suitable locations in NSW for the mineral feedstock

The project objective was to build a mineral carbonation global reference pilot plant that would:

1. Scale up the throughput of CO_2 processing
2. Generate information about the integration, economics and energy requirements
3. Generate enough product rocks to assess the feasibility of manufacturing useful materials
4. Assess the partitioning of secondary ores
5. Make carbonation less energy intensive and less expensive

Details of these outcomes and descriptions and the results achieved against each one are attached.

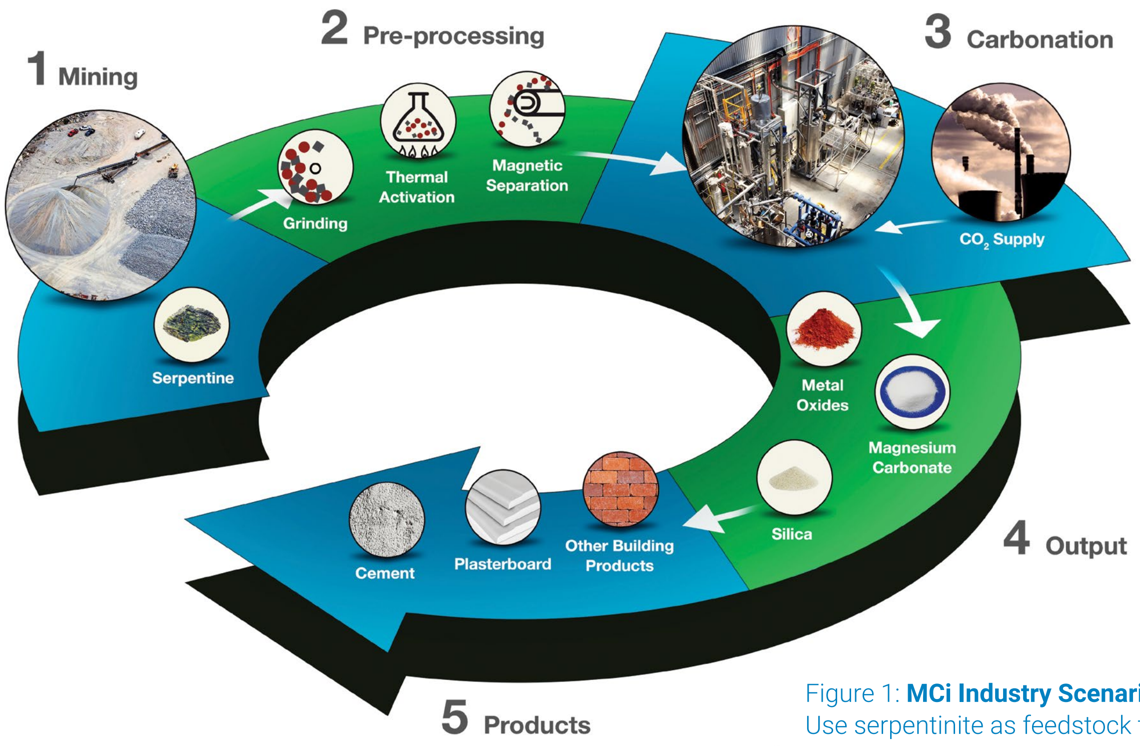
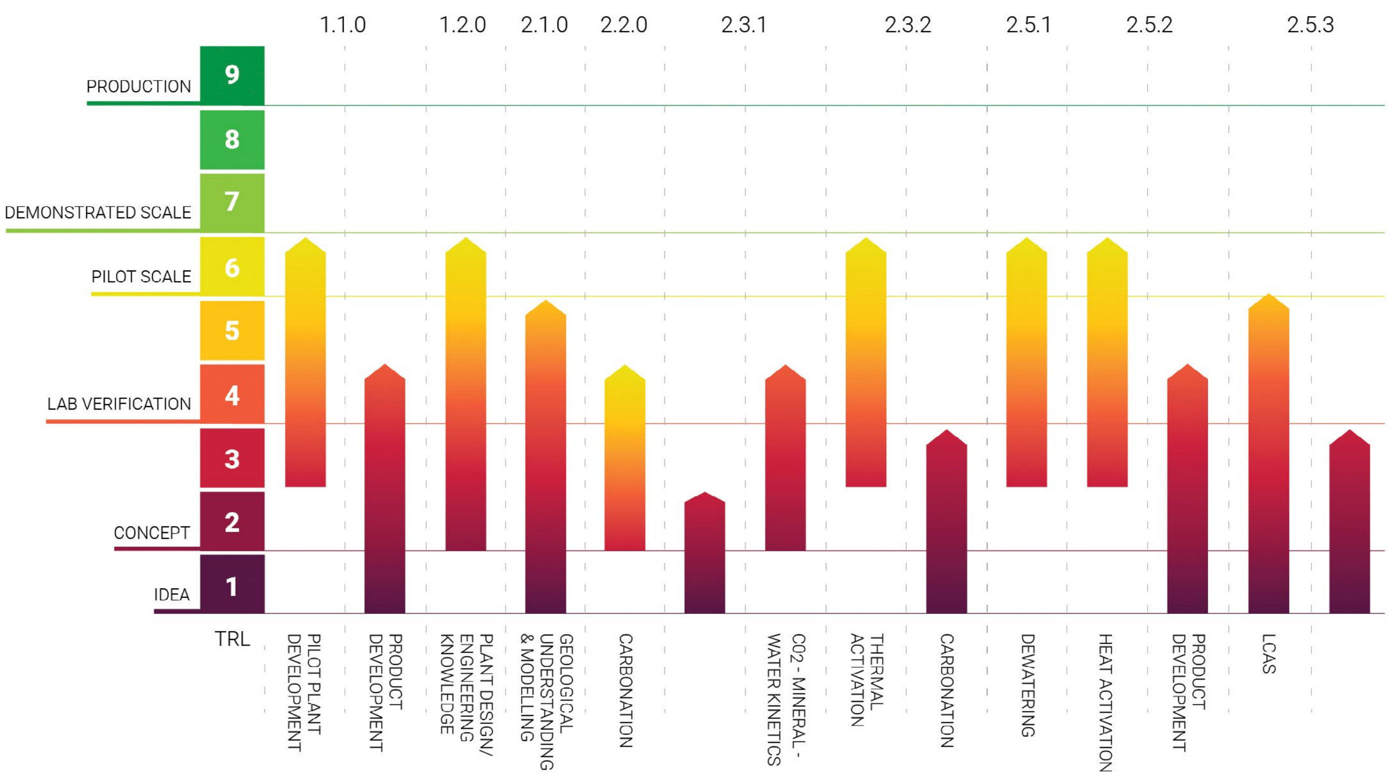


Figure 1: **MCi Industry Scenario:** Use serpentinite as feedstock to create building products

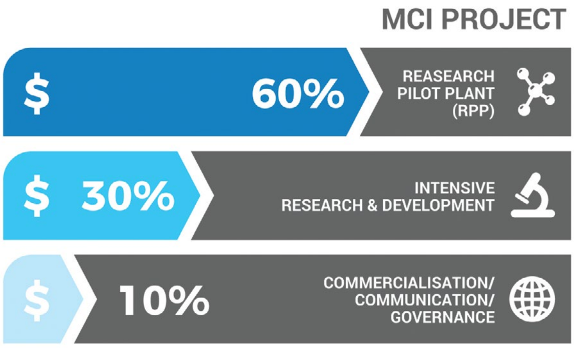
Technology Readiness Levels of each of MCi's Technology Strands in its Platform



The 14 scientific and engineering strands conducted during the project.

This model for TRL is based on the European Association of Research and Technology Organisations model in "The TRL Scale as a Research & Innovation Policy Tool, EARTO Recommendations", 2014.

Executive Summary (Cont.)



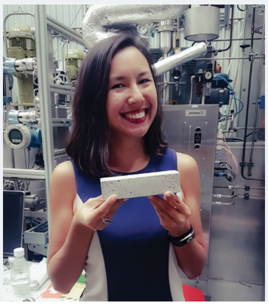
The MCi project was conducted in three strands: the research pilot plant (RPP), intensive R&D aimed at improving and optimising the process and a commercialisation/communications/governance strand, with the buţet allocation approximately 60/30/10 for the three strands, respectively.

An early foundation decision was taken to handle only material that had been tested and certified as fibre-free. This formed the basis of a geological project to identify suitable serpentinite that contained no fibres, both for the RPP and for possible future mining in NSW. This project evolved into a PhD program that developed a methodology for predicting the likelihood of occurrence in an orebody. The method was successful in enabling MCi to obtain sufficient quantities of ore, some 20 tonnes, for the operation of the RPP.

The mineral carbonation process (refer to Figure 1) involves mining, crushing and grinding the ore into a powder, prior to thermal activation which enhances the reactivity between the mineral and CO_2. After activation, the material is carbonated by first combining the powder with water to make a slurry and then a ing CO_2. Two carbonation processes were investigated as part of the project, the ARC process and a novel two-stage process developed in the project that operates at near ambient conditions (< 10 bar, < 50 °C). Carbonation of serpentinite produces magnesium carbonate and silica, that were tested for use in various construction products including plasterboard and cement. As equipment for crushing, grinding and thermal activation is relatively standardised, it was more economical to conduct these activities using contractor equipment and to focus our efforts and resources on constructing new equipment for the key carbonation part of the process.

The RPP was housed at the Newcastle Institute for Energy and Resources (NIER) site at UON. The design philosophy for the RPP included a modular approach to provide flexibility and to allow independent optimisation of unit operations. Both a batch and a continuous carbonation plant were built. The former was based on a Hastelloy agitated reactor vessel while the latter comprised a bubble column reactor. Scales were two orders of magnitude greater than the laboratory, allowing for a nameplate capacity of some 150 t CO_2 pa. Despite a major setback when the German manufacturer of the batch plant went into administration, MCi was able to successfully negotiate and secure a completed reactor. The continuous plant was designed using components that could be sourced from Australian suppliers. The Orica Hazard Study methodology was adopted in the MCi project for both plant design and constructions to manage risk.

The research strand was centred at UON where macro-scale heat activation and carbonation were undertaken, while the University of Sydney focussed on micro-scale fundamentals. Columbia University investigated potential a itives and low-pressure carbonation. As the most abundant feedstock in NSW, lizardite serpentinites were the focus, with some work also conducted on dunite. The former required heat activation while the latter required further grinding. Following extensive work, heat activation of the lizardite was optimised, and a provisional patent was filed. However, despite optimal activation, it was found that conversion of the lizardite serpentine to carbonate was limited in the ARC/NETL process to around 50%. To assess the RPP for treating alternative, globally available feedstocks, olivine was also imported and tested. It was found that over 80% conversion could be achieved in 3 hours. This conversion extent was in agreement with the laboratory R&D conducted by the ARC/NETL, however the reaction rate was somewhat slower.



Hydrated magnesium carbonate, nesquehonite, was obtained as a separable product, in a ition to a silica-rich product. The former has potential as a fire-resistant component in plaster-based building products while the latter was tested as a pozzolan in cement mortars. Replacement of 5% of Portland cement was successful without any optimisation of the silica in testing and experimental work conducted with Boral as an industrial partner.

Global cement production is currently around 4,000 million tonnes p.a. (Source: https://www.statista.com/statistics/267364/world-cement-production-by-country/) Replacement of 5% by MCi silica would results in a global market size of 200 million tonnes per year. Australian cement production is currently at about 10Mt p.a. (Australian Cement Industry Statistics 2017, http://www.cement.org.au/AustraliasCementIndustry/CIFFastFacts.aspx), which would allow to replace 0.5 Mt p.a. by MCi silica within Australia.

Life Cycle Assessments (LCAs) were conducted on various scenarios of mineral carbonation linked to coal-fired power generation in a NSW setting. It was found that if a 75% conversion could be achieved, then mineral carbonation was competitive with, or superior to, geosequestration in terms of net GHG emissions per MWh delivered to the grid.

A comprehensive techno-economic feasibility study of the process was conducted and detailed plant costings. In our LCA on this process, we estimate a net profit of \$240/t CO_2 stored may be achieved in a scaled plant of 250 ktpa. This now forms a core part of the follow-on research and development for MCi.

Without the need for a carbon price, a plant built at scale could yield a net profit of around A\$240/t net CO_2 stored.

ACADEMIC ACHIEVEMENTS

The MCi project supported six PhD programs and three Postdoctoral research fellows. More than twenty papers were published in journals and research conferences. A full list is attached.

COMMERCIALISATION ACTIVITIES

Project IP was largely gathered in the form of know-how of plant design and operability and as such was kept in-house. One patent application reached national phase and two further provisional patents were filed, while a further two are under development. MCi is seeking to license Orica's two international patent families on heat activation of serpentinite.

Early commercialisation activities have been conducted throughout the project term with several opportunities progressed in Australia and in Singapore for private investment and advancement of the technology into demonstration projects.

CONCLUSIONS AND FUTURE DIRECTIONS

The project was successfully conducted on budget and within agreed timeframes. While the scale-up and continuous operation of the ARC/NETL process was successfully achieved, there were limitations. Olivine and other feedstocks, such as steel slag, may be viable alternatives in this process and MCi plant technology could be employed for these feedstocks. This has set MCi on course to further develop this process, with funding from a Commonwealth CRC-P program currently being directed at processing flue gas directly. Future work will be directed at optimisation of the economic value of the products.

01 Outcome One

Decrease the cost for storing CO_2 by mineral carbonation from \$70 to \$40 per tonne (or less) of net fixed CO_2 *(note that the baseline cost has been revised from \$70 to \$243 per tonne of net fixed CO_2 owing to changes in input costs since 2008. These include a doubling of electricity price, tripling of gas price, US \$ to AU \$ conversion, halving of saleable iron ore price, improved accuracy of other costs and inclusion of Scope 3 emissions which had previously been neglected. The corresponding revised target outcome is \$137/tonne. Details are in a separate techno-economic LCA report in Appendix A).*

The outcome was achieved with a net revenue of \$240 per net tonne CO_2 for the newly developed two-stage mineral carbonation process based on an average product price of \$100 per tonne of output material.

The two-stage process is at an early stage of development and was devised in response to low reaction yields observed with the single-stage high pressure, high temperature process (known as the ARC process) that formed the basis of the funding proposal. The two-stage process therefore requires further investment and scale up to verify and demonstrate these costs at pilot scale.

The project generated cost reductions of \$115 per tonne of CO_2 for the ARC process assuming the same reaction yield as the baseline analysis. The cost improvement was offset by the low carbonation yield of NSW serpentine ores relative to that reported in the literature, resulting in a total cost of \$350 per tonne for that process.

TWO STAGE PROCESS INCLUDING PRODUCT SALES

The new two-stage process developed in the project provides an inherent separation of silica rich and magnesium carbonate products, providing a significant offset to the cost of CO_2 storage. Indicative storage only costs for different average product prices demonstrate that the target cost of \$137/tonne CO_2 is achieved at a product price of approximately \$30/tonne, which is below current market prices.

ARC PROCESS:
BASE CASE INCLUDING IMPROVEMENTS – 75% CONVERSION

We identified and verified several improvements to the ARC process, reducing the cost to $128 per net tonne stored under the assumption that 75% reaction yield can be achieved. These included:

- Capture of emissions from heat activation, saving $29/tonne
- Heat integration between amine capture and MCi process, saving $35/tonne
- Optimisation of heat activation, saving $26/tonne
- Energy recovery from high pressure slurry and improved grinding efficiency, saving $25/tonne

ARC PROCESS:
FINAL RESULT INCLUDING PILOT PLANT DATA

Reaction yields for the ARC process were lower than reported in the literature and assumed in the baseline analysis (50% versus 75%). The low yield requires a larger quantity of rock to be processed, increasing heat activation, grinding and capital costs, resulting in an overall cost of $350 per tonne.

OLIVINE:

A cost estimate was produced for olivine feedstock based on experimentally determined grinding energies and literature reported reaction yields, resulting in a cost of $120 per tonne of CO_2 stored. The olivine case was based on literature values of extensive carbonation experimentation (by the ARC). Due to time constraints, only very limited carbonation experiments could be conducted with olivine.

02

Outcome Two

Decrease the energy intensity from 252 kg CO_2/tonne CO_2 sequestered to 150 kg CO_2/tonne CO_2.

The outcome was achieved for olivine feedstock with an estimated energy/emissions intensity of 129 kg CO_2 per net tonne stored.

For the ARC process using serpentinite feedstock, an emissions intensity of 118 kg/net tonne stored could be achieved with a reaction yield of 75%. Unfortunately, the yields observed for NSW serpentine ores in the ARC process were lower than desired, resulting in an emissions intensity of 298 kg/tonne stored. The emissions intensity for the MCi two-stage process was 232 kg/tonne stored, however, there is significant potential to reduce this through direct use of flue gas and by accounting for the lifecycle benefits of the products.

UPDATED BASELINE ANALYSIS:

The baseline emissions factor was updated, resulting in an increase from 252 to 424 kg/tonne stored, owing to:

- Inclusion of scope 3 emissions within the system boundary, increasing emissions by 69 kg CO_2 per tonne stored.
- Improved estimate of electricity consumption (milling, pumping, compression), increasing emissions by 103 kg CO_2 per tonne stored.

ARC PROCESS: MCI IMPROVEMENTS – 75% CONVERSION

The base-case scenario also incorporated several improvements relative to the original analysis, resulting in emissions of 118 kg/tonne CO_2 stored owing to the following factors:

- CO_2 produced from the combustion of natural gas for heat activation (HA) is captured and stored, reducing emissions by 174 kg/tonne stored.
- Heat released by the carbonation reaction is recovered to offset the energy required for post combustion capture, reducing the capture heat requirements by approximately 50% and reducing emissions by 102 kg/tonne stored.
- Slurry energy recovery, optimised grinding and optimised heat activation reduced emissions by 30 kg/tonne stored, despite the higher flow of rock to process HA CO_2 emissions.

The total emissions from a typical NSW power station, including amine post combustion capture and mineral carbonation storage are 281 kg/MWh of electricity sent to the grid.

ARC PROCESS BASED ON PILOT PLANT DATA AND ADDITIONAL PROCESS IMPROVEMENTS

Reaction yields achieved in the ARC process were lower than reported in the literature and assumed in the baseline analysis. The low yield requires a larger quantity of rock to be processed per tonne of CO_2 stored, increasing heat activation and grinding emissions, with an overall result of 298 kg/net tonne stored.

TWO-STAGE PROCESS

The MCi two-stage process has an emissions intensity of 232 kg/net tonne stored, despite achieving a high reaction yield. Relative to the ARC MCi improvements case, emissions for the two-stage process are higher, as the exothermic heat of reaction released at 45 °C is not able to be utilised in the amine capture process. The two-stage process is still in the early stages of development with significant potential to improve the energy and emissions intensities, by direct use of flue gas in the process, further process optimisation and accounting for the lifecycle benefits of the products.

OLIVINE

The ARC process with olivine feed achieves a favourable emissions intensity of 129 kg/net tonne stored owing to high reaction yields. The energy emissions for ultra-fine grinding are offset by the fact that the ore does not require heat activation.

03

Outcome Three

Develop new, and improve the existing, unit operations to optimise the process and test these unit operations in the demonstration plant.

The objective was achieved with the project developing, constructing and optimising the design and operation of several unit operations in the research pilot plant.

MCi Engineers in front of pilot kiln

Innovations were made to all key unit operations of the process, the main highlights are outlined below:

TWO-STAGE PROCESS

We developed a new multiple stage low temperature and pressure process that achieves high reaction extents (up to 75% yield for GSB lizardite) under benign conditions which was based on a original multistage process first proposed by ETH Zurich. Both steps of the process were demonstrated at pilot scale for the first time in the batch autoclave reactor, with results significantly exceeding those previously reported in the literature and those of the ARC process. We achieved 75% conversion compared to around 50 % in the ARC process.

THERMAL ACTIVATION

Thermal activation was conducted at pilot scale in both rotary kilns and fluidised bed calciners. The operating parameters in the kiln were optimised, including inclination angle, rotation speed, shell temperature and product feed rate. New designs were successfully demonstrated at pilot scale. The improvements and optimisation are relevant to both the two-stage and ARC process.

HIGH EFFICIENCY GRINDING MILL

We operated the novel High Efficient Grinding (HIG) Mill successfully at pilot scale and optimised the mill media and conditions to maximise energy efficiency. We demonstrated a 70% reduction in grinding energy for a product size of 37 microns relative to the previous best available data from the ARC based on conventional technology. This reduces process energy requirements and emissions and makes it more practical to achieve much finer particle sizes (and consequently higher reaction rates) than previously thought possible. The unit operation is suitable for milling fresh material, or regrinding of partially reacted product in both the two stage and ARC process.

CARBONATION REACTOR

The project demonstrated for the first time the successful operation of a continuous pilot scale carbonation reactor, which achieved the same product yield as the previously employed pilot-scale stirred batch reactor system. The reactor is a much simpler design, with no external agitation or dynamic seals, decreasing the cost and complexity of this unit operation and is hence suitable for both the ARC and two-stage processes.

HYDROCYCLONES

The aim of the hydrocyclone system is to separate carbonated material from partially reacted serpentine particles, so that partially reacted material can be recycled (and re-milled) to improve the overall carbonate yield. Prior to the project, no data on serpentinite slurry separation were available. We constructed a hydrocyclone test rig that enabled the unit operation to be improved and optimised. A separation model was developed and validated using experimental data, demonstrating accurate prediction of the particle size distribution and the solid concentration of the products.

REMOVAL OF NaCl

We optimised the reactor unit operation by eliminating the troublesome sodium chloride (NaCl) a itive from the ARC process, demonstrating that this does not negatively impact performance. Removing NaCl reduces reagent costs and capital costs, allowing for cheaper steels to be used as stress corrosion cracking becomes less likely.

04

Outcome Four

Identify and optimise the production of offsets, such as pavers and bricks or metal ores.

The outcome was achieved with two new products developed in addition to the metal ores identified in previous work.

MAGNESIUM CARBONATE WALLBOARDS

The project identified the potential to produce plasterboard products from hydrated magnesium carbonate materials. Nesquehonite, a hydrated form of magnesium carbonate ($MgCO_3{\cdot}3H_2O$) produced in the batch reactor was used to generate magnesium carbonate-based plaster samples for compression strength testing. Activated nesquehonite was shown to exhibit cementitious properties when combined with water. Initial optimisation including the effect of water content and calcination temperature was conducted.

The energy required for dehydrating nesquehonite was quantified and found to be comparable on a mass basis to gypsum (used in conventional plasterboard products). Owing to its lower density, plasterboard produced with nesquehonite will consume less energy during manufacture than conventional products, in a ition to containing up to 30% CO_2 in its structure. Further work beyond the scope of this project is required to conduct a itional testing and to develop a manufacturing process for the new products.

The global gypsum market was valued at $1.49 billion in 2016, equivalent to 252 million tonnes pa, with 33.3% being consumed in the plasterboard industry, i.e. 84 million tonnes pa.

Nesquehonite ($MgCO_3{\cdot}3H_2O$) plaster is a potential substitute for gypsum in plasterboard products with attractive physical characteristics such as fire retardance, thermal insulation and non-toxic emissions in fire. Asia has a shortage of gypsum.

This was forecast to grow at a CAGR of 9.9% to reach nearly $2.4 billion by 2018 and $3.8 billion by 2026, equating to 135 million tonnes pa by 2018 and 214 million tonnes pa by 2026 in plasterboard. (https://www.smithersapex.com/news/2016/february/global-gypsum-market-set-for-growth) A carbonation plant for a 660MW power station could produce a maximum of about 14 million tonnes pa of nesquehonite.

AMORPHOUS SILICA FOR CEMENT

The project identified cement and concrete as potential applications for amorphous silica produced as a by-product of serpentinite carbonation. Through a collaboration with Boral, the performance of a range of by-product materials prepared using various methods was assessed in laboratory mortar tests. Preliminary testing indicated that mineral carbonation by-products could replace between 5-10% of the cement content in the mortars without impacting their performance.

Global cement production is around 4000 million tonnes pa (Source: https://www.statista.com/statistics/267364/world-cement-production-by-country/) Replacement of 5% of this by MCi silica gives a global market size of 200 million tonnes pa. Australian cement production is about 10Mt pa (Australian Cement Industry Statistics 2017, http://www.cement.org.au/AustraliasCementIndustry/CIFFastFacts.aspx). This would mean up to 0.5 Mt pa could be replaced by MCi silica within Australia.

The global specialty silica market was estimated at USD 2.66 billion in 2016 and is expected to grow at a CAGR of 4.9% through to 2022. Increasing rubber consumption in tyre manufacturing, most notably in Asia Pacific, is expected to have a positive impact on the industry (Source: https://www.grandviewresearch.com/industry-analysis/specialty-silica-market). For a low end estimate of tonnages, we assume an average sale price of $1000/t, yielding a market of 3.2 million tonnes pa in 2020.

Cement mortars containing MCi products

As above, a carbonation plant for a 660MW power station could produce a maximum of about 7 million tonnes pa of silica.

The amorphous silica could also be refined for use in other high value products, with the potential to be sold for $US400-$1000 per tonne. This gives MCi an opportunity to recover significant costs from the process. One such market for this silica is green tyres which contain silica to provide low rolling resistance.

Global markets for plasterboard and silica as a cement replacement are around 160 and 200 million tonnes pa, respectively and are steadily growing. MCi's development roadmap requires the sale of products representing less than 1% of these markets for a large scale carbonation plant servicing a 660MW coal power station.

05

Outcome Five

Identify suitable locations in New South Wales for sourcing feedstock for the demonstration plant and subsequent opportunities for larger scale operations.

The outcome was achieved, with over 20 tonnes of feedstock sourced for the pilot plant.

Previous work by Davis (2008) has shown the GSB serpentinites are available in sufficient quantities to sequester hundreds of years of NSW emissions. A 100 km section of the great serpentinite belt was surveyed, and a 7 km stretch mapped in detail. This identified areas of high purity lizardite type serpentinite with suitable mineralogy that are most suited to a future large-scale operation.

PLANT FEEDSTOCK

Rock samples were collected from various accessible sites in the Great Serpentine Belt (GSB), Coolac Serpentine Belt, Glenrock and Mt George areas to determine their suitability for use in the pilot plant. Samples were subjected to petrographic analysis to characterise their mineralogy and purity. Two sites in the GSB were identified as being readily accessible, fully serpentinised and asuitable for our process. Sample site 1A was characterised as lizardite, whilst sample site 3A was identified as antigorite. The lizardite showed the highest reactivity in laboratory tests and was selected for the first bulk sample. Approximately 100 tonnes were excavated, of which 11 tonnes were milled for heat activation trials.

The bulk sample was subsequently found to contain an impurity mineral (clinochlore) that was not present in the initial samples, which negatively impacted its reactivity. In response, a second 11 tonne bulk sample was sourced, yielding a total of 22 tonnes of material for heat activation/carbonation trials.

LARGER SCALE MAPPING

Initial work focused on determining the broad trends in the mineralogy along a ~100 km stretch of the GSB from Bingara to Attunga, north of Tamworth. These results were summarised into a series of maps of the surface geology within the four largest serpentinite bodies.

Within the northernmost serpentinite body of the GSB, a 7km long (8 km^2) site was selected for further detailed mapping.

Extraction of rock sample for pilot plant

Strand 1.1.0 Final Report

Research Pilot Plant Construction and Operation

SUMMARY

This project aimed to design, build and operate a research pilot plant to demonstrate the feasibility of applying direct aqueous carbonation technology on an industrial scale by reacting CO_2 with heat activated mineral sourced from the NSW Great Serpentinite Belt. The pilot plant development was split into two design stages — batch and semi-continuous plant — to minimize the risks involved in upscaling bench scale research facilities and designing novel, industrial scale carbonation technology. Overall performance, cost, energy and greenhouse efficiency data were collected to conduct life cycle assessments of the technology and sufficient quantities of carbonated products were generated to investigate their applicability in novel construction materials.

RESEARCH IMPACT ON TECHNOLOGY DEVELOPMENT

CO_2 Cost Reduction	Scale Success	IP Contribution	Overall Success Score
50%	**100%**	**10%**	**100%**

PROJECT OBJECTIVES AND TECHNICAL OUTCOMES

Design, build and operate research pilot plant for aqueous carbonation with a nominal capacity of 30 tonnes CO_2 per year.

Two pilot plant units have been developed and operated successfully with a combined nominal capacity of 150 tonnes CO_2/year sequestered. The biggest accomplishments of the project were the realisation of a world first bubble column carbonation reactor on pilot scale and the development of novel unit operations and process conditions.

Obtain overall performance, cost, energy and greenhouse efficiency data for life cycle analyses (LCAs) of the technology and deliver knowledge-base for design of continuous demonstration plant.

Successful operation of both pilot plant units provided comprehensive performance data and analytical results that formed the data base for subsequent life cyle analyses and feasibility studies. The technical knowhow gained throughout the process was incorporated in the conceptual design of a demonstration-scale plant.

Sufficient scale-up from lab scale to prove the applicability of the carbonation technology by a factor of 30.

Both pilot reactors were sized to achieve a significant scale-up from previous bench top carbonation equipment. Scale-up factors of 50 for the batch plant and 200 for the semi-continuous plant were achieved to provide relevant process data for future larger scale applications.

Determine and test suitable heat activation methods and provide mineral feedstock for the pilot plant.

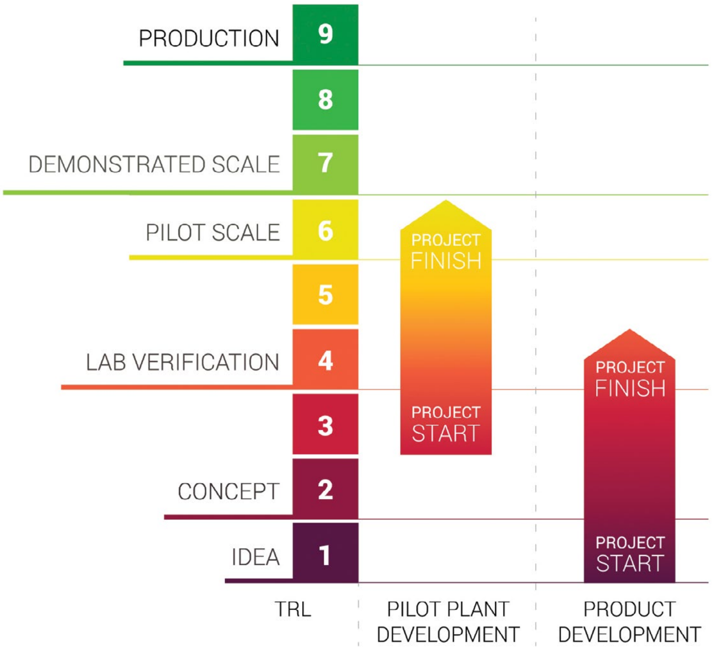
8 tonnes of serpentine feedstock from the NSW Great Serpentinite Belt were processed in two pilot heat activation campaigns for use in the pilot plant. Optimised conditions for the thermal treatment were delevoped in the lab and have been applied successfully at pilot scale at a throughput of 1.4 tonnes per day.

Provision of sufficient quantities of carbonated output to test suitability for potential products.

Several hundred kg of magnesium carbonate and silica rich reaction products were provided to assess their application in building products such as concrete and plasterboard.

Mineral carbonation pilot plant at the University of Newcastle

TECHNOLOGY READINESS LEVEL



FINANCIAL SUMMARY

Budget item	Budget costs	Actual Expenditure
Income	**$4,790,000.00**	**$4,790,000.00**
Management fee	$479,000.00	$474,000.00
Employment costs	$593,000.00	$1,046,161.09
External Resources	$490,000.00	$795,363.63
Expenses Batch	$1,000,000.00	$935,516.24
Expenses SCR	$1,328,000.00	$980,464.89
Consumables	$900,000.00	$311,890.14
Total:	**$4,790,000.00**	**$4,543,395.99**
		$246,604.01

PROJECT CHALLENGES

Unforeseeable supply difficulties of custom-design equipment from overseas caused significant delays in the project schedule.

The abrasive nature of the slurry made slurry pumping and depressurising challenging, requiring the design of customised engineering solutions.

GAPS

Difficulty in sourcing high quality ore meant that sub-optimal feedstock material was used in the process. Testing with higher quality feed material would improve process performance.

NEXT STEPS

Modify the pilot plant for the two-stage process to sequester simulated flue-gas.

Demonstrate the application of two-stage process products in construction materials, and optimise the process to maximise product value.

COMMENTARY

Savings realised from both pilot plant constructions and procurement of feedstock and consumables were put towards a itional technical support from Orica and employment of a itional staff for plant operation and chemical analyses to compensate for delays caused during procurement of the batch plant equipment. The project was under buţet at completion.

Strand 1.2.0 Final Report

Continuous Plant Concept Design and Feasibility Study

SUMMARY

The project aimed to produce a design, techno-economic feasibility study and lifecycle assessment for a continuous mineral carbonation plant based on the knowleţe gained from the research pilot plants and research projects. The project was completed successfully with numerous innovations in the design.

RESEARCH IMPACT ON TECHNOLOGY DEVELOPMENT

CO_2 Cost Reduction	Scale Success	IP Contribution	Overall Success Score
80%	**N/A**	**10%**	**100%**

PROJECT OBJECTIVES AND TECHNICAL OUTCOMES

Develop a concept design for continuous demonstration plant for aqueous carbonation

We completed concept designs for mineral carbonation plants integrated with coal fired electricity generation at full scale (>660 MW).

A concept design was completed for a demonstration scale (250 ktpa) two-stage process plant.

LCA for continuous plant design

Improvements from the MCi program would result in a reduction in emissions intensity from 373 to 116 kg/tonne for the ARC process, assuming constant conversion to carbonate. The low conversions observed result in an emissions intensity of $298 /net tonne stored.

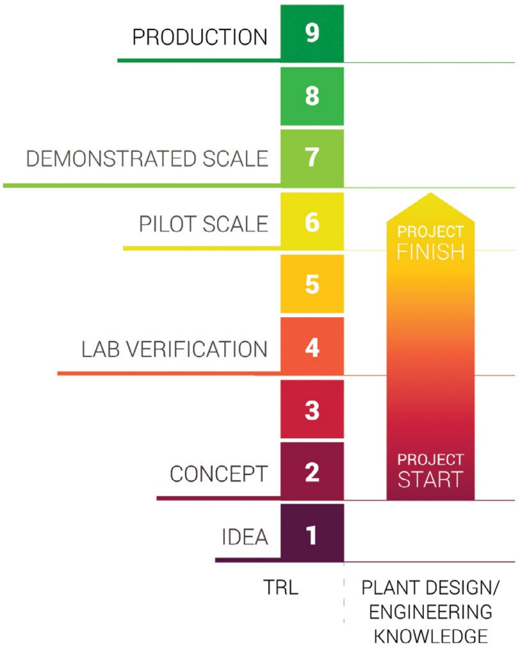
The two-stage process has an emissions intensity of 232 kg/ tonne stored, which could be significantly reduced by accounting for product lifecycle benefits and through direct use of flue gas in the process.

Preliminary economic analysis

The two-stage process has the potential to yield returns of ~$200 / net tonne stored subject to further product development.

Poor reaction conversions in the ARC process resulted in a storage cost of $350 /tonne of CO_2 despite cost reductions of $115 /tonne identified in the MCi program.

TECHNOLOGY READINESS LEVEL



FINANCIAL SUMMARY

Budget item	Budget costs	Actual Expenditure
Income	**$490,000.00**	**$490,000.00**
Management fee	$ -	$44,000.00
External Resources	$400,000.00	$195,526.21
LCA, feasibility study, final report	$90,000.00	$131,716.07
Total:	**$490,000.00**	**$371,242.28**
		$118,757.72

PROJECT CHALLENGES

The low conversions achieved in the ARC process had a significant negative impact on the cost and energy intensity of that process. This was a ressed by the development of the two-stage process.

GAPS

The two-stage process has potential to be profitable but requires further product development.

Data is required on the performance of the two-stage process with flue gas and the lifecycle benefits of the products to improve the accuracy of the economics and LCA of that process.

Cost for cyclone coolers for heat activation energy recovery are conservative and could benefit from a itional quotations and/or greater engineering detail.

COMMENTARY

The project was conducted well under buţet.

Strand 2.1.0 Final Report

Mineralogy of Raw Material Feedstock

SUMMARY

The project aimed to identify sources of fibre-free or low-fibre risk serpentinite rocks for use in MCi projects. All objectives were achieved, including the development of a geostatistical model of mineral fibre distribution.

RESEARCH IMPACT ON TECHNOLOGY DEVELOPMENT

CO_2 Cost Reduction	Scale Success	IP Contribution	Overall Success Score
0%	**75%**	**10%**	**75%**

PROJECT OBJECTIVES AND TECHNICAL OUTCOMES

To identify fibre free serpentinite rocks for use in MCi project.

~22 tonnes of fibre free serpentinite (Sample 1A) was collected from the NSW Great Serpentinite Belt that provided sufficient amounts of feedstock for the operation of the RPP.

To identify deposits with the highest potential to produce valuable metal products.

Small scale pods of chromite and dunite rich pods have been mapped, these pods contain the highest concentration of chromium and vanadium relative to the bulk serpentinite.

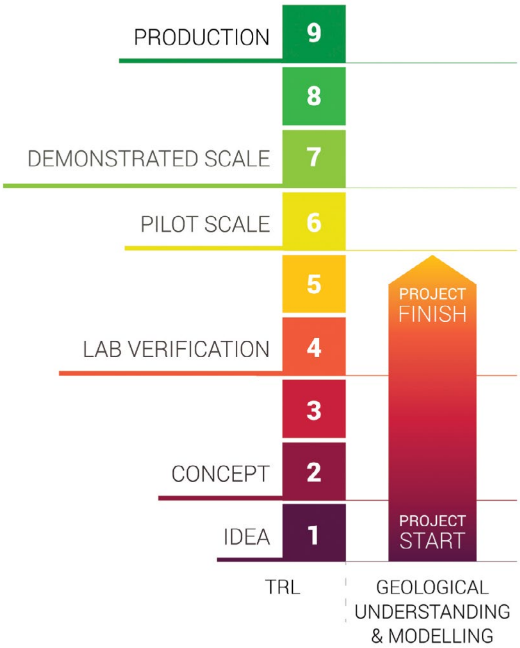
To develop geological models to predict locations with lowest fibre risk.

Regional scale mapping identified highly sheared regions to be the most prospective for large scale mineral carbonation. Surface mapping within these regions indicated clusters in mineral fibre veining intensity within phacoidal bodies (relatively competent bodies within the sheared rock).

To identify suitable locations for future large-scale serpentinite extraction for mineral carbonation.

A 100 km section of the Great Serpentinite Belt was mapped including detailed surface measurements of a prospective 8km^2 section indicating large contiguous sheared regions to be low-fibre risk, suitable for use in larger projects.

TECHNOLOGY READINESS LEVEL



FINANCIAL SUMMARY

Budget item	Budget costs	Actual Expenditure
Income	**$450,000.00**	**$450,000.00**
Management fee	$45,000.00	$44,500.00
Employment costs	$192,000.00	$252,357.31
Analysis	$50,000.00	$66,035.27
Mining, Transport, Crushing	$110,000.00	$44,090.50
Travel and Conferences	$53,000.00	$42,516.92
Total:	**$450,000.00**	**$449,500.00**
		$500.00

PROJECT CHALLENGES

Current approaches to field data collection are labour-intensive limiting the scalability of mapping. Automation or a more efficient workflow will be required to reach increased production.

GAPS

The degree to which fibres are preserved or redistributed during shearing is unknown, this results in uncertainty of measurements at low concentrations of fibres.

COMMENTARY

This project was initially conducted with a Masters student however due to his dedication and interest for novel research, the student converted to a PhD and we are developing a provisional patent based on his geostatistical model. This strand progressed 5 levels of TRL.

Strand 2.2.2 Final Report

Macro-scale Carbonation

SUMMARY

The project aimed to determine the optimal conditions for carbonation of serpentinite samples. The objectives were achieved, however, the project was not able to reproduce the level of conversion reported in the literature for the ARC (high pressure) process. This was subsequently mitigated by the development of the two-stage process in strand 2.5.3. Laboratory results were reproduced successfully at pilot scale.

RESEARCH IMPACT ON TECHNOLOGY DEVELOPMENT

CO_2 Cost Reduction
-100%
(ie. cost increase)

Scale Success
50%

IP Contribution
0%

Overall Success Score
25%

PROJECT OBJECTIVES AND TECHNICAL OUTCOMES

To design, build and operate macro scale apparatus to carbonate serpentinite.

Two separate 300mL and 600mL high pressure reactors and associated gas manifolds were designed, installed, commissioned and operated safely to carbonate serpentinites.

To optimize the carbonation of serpentinite.

Carbonation of dunite and lizardite feedstocks was optimised by conducting experiments at a range of temperatures, pressures, solution compositions and particle sizes. The maximum lizardite conversion was 50% for which ultrafine grinding was required, significantly lower than the literature and negatively impacting the economics of the process.

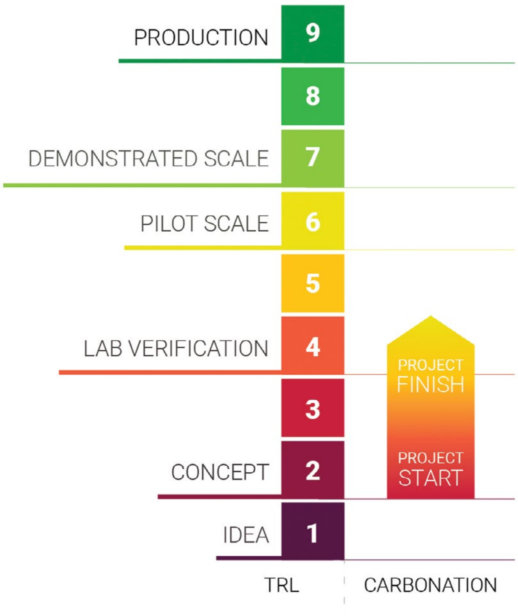
To develop analytical techniques to determine optimal mineral carbonation processes.

A thermogravimetric analyser (TGA) was coupled with a mass spectrometer (MS) to enable accurate determination of magnesite yields, in conjunction with quantitative X-ray diffraction.

To modify the macro-scale reactor with a continuous sampling manifold.

The modification was successfully conducted enabling a better understanding of the mineral carbonation kinetics and the evolution of solid and aqueous compositions during the reaction.

TECHNOLOGY READINESS LEVEL



PROJECT CHALLENGES

Despite optimising the thermal activation process to maximise the amorphous content in 2.5.2, this project was not able to achieve the expected conversion of lizardite feedstock into carbonate. This negatively impacts the economics of the process, as larger quantities of mineral are required per ton of CO_2 stored.

GAPS

Further research is needed to understand and optimise the carbonation process under lower pressure and temperature conditions suitable for the two-stage process.

FINANCIAL SUMMARY

Budget item	Budget costs	Actual Expenditure
Income	**$500,000.00**	**$500,000.00**
Management fee	$50,000.00	$49,000.00
Employment costs	$274,000.00	$248,619.00
Equipment	$160,000.00	$185,460.00
Consumables & Analyses	$12,000.00	$11,925.00
Travel and Conferences	$4,000.00	$3,996.00
Total:	**$500,000.00**	**$499,000.00**
		$1,000.00

Strand 2.3.1 Final Report

Breakthrough Technologies Columbia University

SUMMARY

This project aimed to investigate breakthrough technologies that could take mineral carbonation to the next level of viability beyond the standard (NETL/ARC) aqueous process, by linking with world leading research being conducted at Columbia University.

RESEARCH IMPACT ON TECHNOLOGY DEVELOPMENT

CO_2 Cost Reduction	Scale Success	IP Contribution	Overall Success Score
0%	**0%**	**10%**	**50%**

PROJECT OBJECTIVES AND TECHNICAL OUTCOMES

To quantify the benefits of the most prospective process chemistry routes developed by Columbia in the field of mixed catalytic systems that enhance both magnesium dissolution and carbonate precipitation as well as dissolving the silica passivating layer.

Extensive work was conducted on several chelating agents (catalysts). Both Mg and Si targeting agents were studied. While improvements in dissolution were observed, the overall benefits were too small to be commercially viable.

To establish performance of these systems on heat treated serpentines for direct and indirect processes. This will enable testing of the most prospective systems in the MCi Research Pilot Plant.

All catalytic systems studied established the performance on MCi's heat treated serpentines for both direct and indirect carbonation processes. However, the benefits did not justify testing on the MCi RPP.

To establish the kinetics of CO_2-mineral-water interactions in a packed column reactor.

Kinetic studies were conducted in two types of reactor, a differential bed reactor and a CO_2 bubbling reactor.

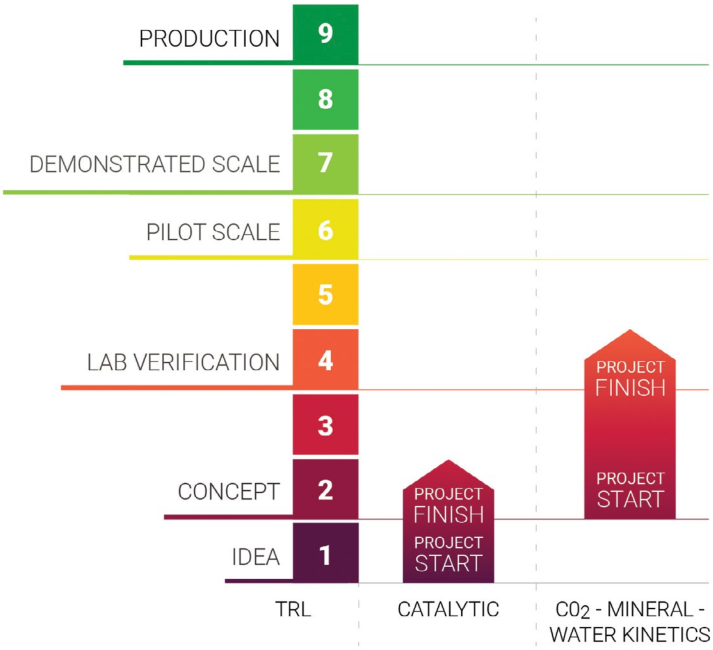
To determine the feasibility of linking air capture systems with serpentine carbonation.

This aspect was a ressed by studies of low pressure CO_2 dissolution. It was shown that dissolution/precipitation could be achieved by CO_2 partial pressure swing.

To determine the feasibility of large-scale ambient systems for heat activated serpentine.

This objective was not pursued as the slow kinetics of ambient carbonation make this an unlikely technology for industrial application.

TECHNOLOGY READINESS LEVEL



PROJECT CHALLENGES

The project lost a Postdoctoral fellow after commencement and was later allocated to two PhD students.

GAPS

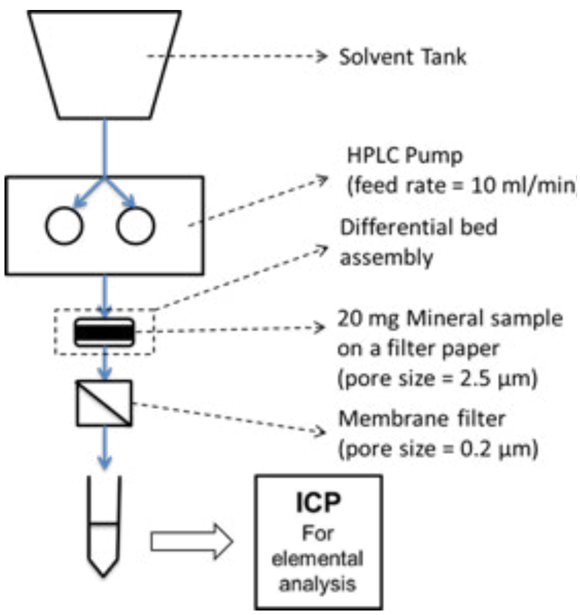
Fundamental understanding of mechanisms of chelating agents interaction with remnant Mg.

NEXT STEPS

Future research could explore the use of ligands in secondary dissolution steps after regrinding.

COMMENTARY

The project was conducted slightly over buţet. This strand was exploratory research seeking breakthrough advances. Outcomes are not predictable nor expected but a to our body of knowleţe.



Differential bed reactor at Columbia

FINANCIAL SUMMARY

Budget item	Budget costs	Actual Expenditure
Income	**$450,000.00**	**$450,000.00**
Management fee	$ -	$45,000.00
Contract payment	$400,000.00	$400,000.00
MCi/NI Resources	$10,000.00	$37,913.36
Professional Services	$40,000.00	$ -
Total:	**$450,000.00**	**$482,913.36**
		-$32,913.36

Strand 2.3.2 Final Report

Micro-Scale Thermal Activation and Carbonation Fundamentals University of Sydney

SUMMARY

This project aimed to investigate the fundamentals of thermal activation and carbonation of serpentinites on the micro scale. The project sought to understand in detail the mineral changes that occur during heat treatment, and to relate these to the reactivity in the carbonation stage.

RESEARCH IMPACT ON TECHNOLOGY DEVELOPMENT

CO_2 Cost Reduction	Scale Success	IP Contribution	Overall Success Score
20%	**100%**	**20%**	**100%**

PROJECT OBJECTIVES AND TECHNICAL OUTCOMES

To understand how mineral changes occurring in thermal activation affect carbonation reactivity.

Extensive work on thermal activation of serpentinite led to a clear understanding of mineral changes, occurring during thermal treatment.

To determine the optimum conditions for thermal activation in terms of temperature, residence time and particle size.

Optimal operating conditions were determined as providing a regime wherein reactivity was maximized. These conditions provided the highest reactivity in carbonation experiments.

To specify carbonation reactivity of the ore as a function of heating rate, reactor temperature and residence times for typical particle size distributions that the MCi process will utilise.

Carbonation reactivity was studied at two temperatures and dissolution mechanisms were elucidated.

To determine the rate limiting step in the carbonation reaction and develop reaction rate laws that account for the effects of temperature, pressure and particle size.

This work identified the factors determining the extent and rate of Mg leaching from calcined serpentines.

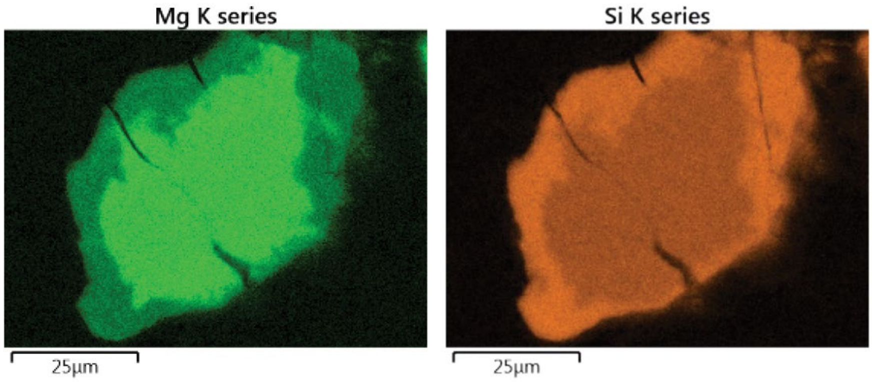
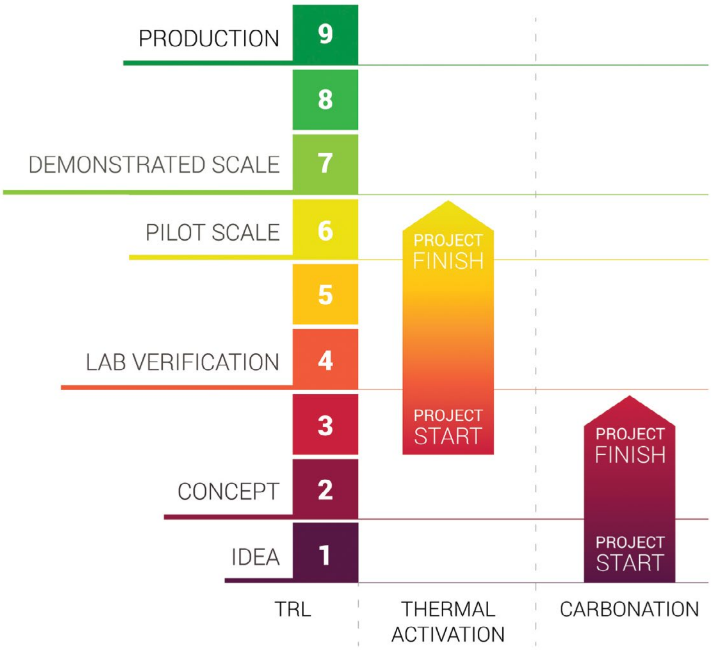


Figure 1. Mg and Si elemental maps (SEM-EDS) of partially leached (X_{Mg} = 67 %), 627 °C calcined SWOL.

TECHNOLOGY READINESS LEVEL



PROJECT CHALLENGES

Elucidating dissolution mechanisms of heterogenous material withmultiple phases and complex mineral structure.

GAPS

Dissolution of remaining Mg in timescales and conditions relevant to an industrial process.

NEXT STEPS

Further R&D could explore mechanisms to extract the remaining Mg although no obvious route currently presents itself.

COMMENTARY

The project was conducted slightly under buţet.

FINANCIAL SUMMARY

Budget item	Budget costs	Actual Expenditure
Income	**$500,000.00**	**$500,000.00**
Management fee	$ -	$50,000.00
Contract payment	$422,000.00	$422,000.00
External Resources	$78,000.00	$18,665.18
Total:	**$500,000.00**	**$490,665.18**
		$9,334.82

Strand 2.5.1 Final Report

Dewatering

SUMMARY

The project aimed to develop low-energy processes for dewatering of the carbonated product from the mineral carbonation process and to determine the optimal method for consolidation of the product for storage. Filtration is the preferred dewatering method owing to the high processing rate and low residual water content of the material. Gravity settling and gravity drainage are too slow to be practical.

RESEARCH IMPACT ON TECHNOLOGY DEVELOPMENT

CO_2 Cost Reduction	Scale Success	IP Contribution	Overall Success Score
0%	**100%**	**0%**	**75%**

PROJECT OBJECTIVES AND TECHNICAL OUTCOMES

To determine the feasible and optimum level of slurry pumping.

Slurry concentrations of 50-55% w/w are feasible to be pumped. Higher solids contents cannot be pumped owing to the risk of solidification that would block a pipe in the event of a pump stoppage

To determine the feasible level of water recovery and dewatering energy requirements for LCA studies.

Low residual water contents are achievable with low energy filtration.

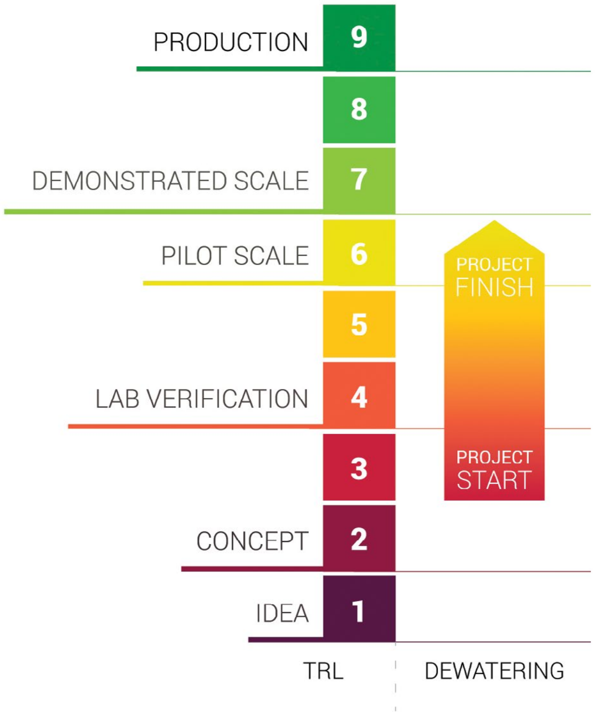
Specific cake resistance properties and water recoveries determined in this project were used in the Strand 1.2.0 LCA and feasibility study to determine the dewatering cost and energy requirements.

To evaluate different process options for slurry dewatering and pumping and develop process schemes that minimise energy consumption and maximize return of process liquor to the plant.

Gravity settling, gravity drainage and filtration were investigated for slurry dewatering with filtration found to be most effective at maximising return of process liquor.

The data gathered was used to determine optimal dewatering schemes in Strand 1.2.0.

TECHNOLOGY READINESS LEVEL



Filter cake

FINANCIAL SUMMARY

Budget item	Budget costs	Actual Expenditure
Income	**$100,000.00**	**$100,000.00**
Management fee	$10,000.00	$9,500.00
Employment costs	$40,000.00	$82,335.93
Equipment	$-	$1,508.00
Professional Services	$50,000.00	$4,162.83
Other	$-	$1,772.36
Travel	$-	$220.88
Total:	**$100,000.00**	**$99,500.00**
		$500.00

PROJECT CHALLENGES

The highly shear thinning nature of the slurry made rheology measurements difficult, with the material transitioning from solid like at rest, to a thin consistency similar to water at high shear rates.

Residual water contents after filtration are still higher than desired, increasing water consumption.

GAPS

Limitations of the equipment made it difficult to accurately determine the effect of temperature on slurry viscosity.

NEXT STEPS

Future work should examine dewatering under conditions relevant to the two-stage process.

Strand 2.5.2 Final Report

Heat Activation and Building Materials

SUMMARY

This project aimed to optimise the thermal activation process of the mineral feedstock serpentinite and develop construction materials from carbonation by-products. All objectives were achieved with the highlight being the successful scale-up of heat activation production rates to 1.4 tonnes / day as a direct outcome of learnings from this research.

RESEARCH IMPACT ON TECHNOLOGY DEVELOPMENT

CO_2 Cost Reduction	Scale Success	IP Contribution	Overall Success Score
20%	**100%**	**25%**	**100%**

PROJECT OBJECTIVES AND TECHNICAL OUTCOMES

Design, build and operate macro scale equipment to achieve heat activation of Serpentinite.

Acquisition and successful operation of laboratory rotary kiln to investigate the effect of process variables such as temperature, time, heating atmosphere, particle size on material reactivity.

Production of construction product samples for material testing.

Cement mortars from various mineral carbonation by-products were prepared for strength testing with some materials exhibiting improved strength, offering potential to reduce both the cost and greenhouse emissions of cement.

Optimisation of thermal activation of serpentinite with the least energy demand on laboratory scale.

140 heat activation experiements were conducted to maximise material reactivity and minimise energy demand, resulting in successful scale up to a 1.4 tonne/ day production rate for the pilot plant.

Development of analytical techniques to determine optimal heat activation through mineral analysis.

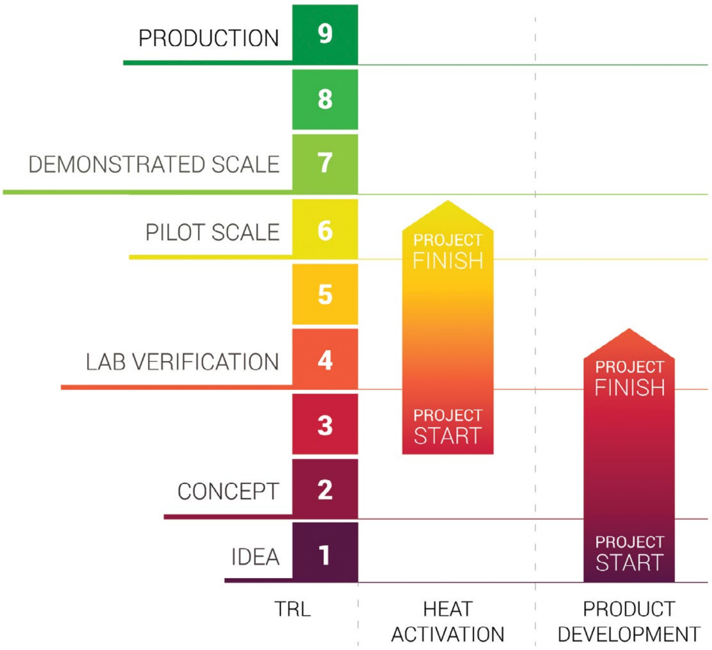
Quantitative X-ray diffraction and thermo-gravimetric analysis were employed to study and optimise the heat activation process resulting in a novel, low-cost method to assess material reactivity successfully in pilot scale trials.

Development of a process to produce valuable construction materials from carbonation by-products.

Processes were developed to produce silica rich and magnesium carbonate materials for use in concrete and plasterboard, respectively. Proof of concept achieved at lab scale.

Cement mortars containing magnesium carbonates used for materials testing.

TECHNOLOGY READINESS LEVEL



GAPS

Plasterboard materials require further research to progress from the laboratory to pilot scale.

NEXT STEPS

Partner with companies to optimise products for markets and a ress technical challenges.

Advanced manufacturing funding being sought.

FINANCIAL SUMMARY

Budget item	Budget costs	Actual Expenditure
Income	**$400,000.00**	**$400,000.00**
Management fee	$40,000.00	$38,500.00
Employment costs	$262,000.00	$183,277.00
Equipment	$80,000.00	$67,600.00
Consumables & Analyses	$14,500.00	$103,883.00
Travel and Conferences	$3,500.00	$5,240.00
Total:	**$400,000.00**	**$398,500.00**
		$1,500.00

Strand 2.5.3 Final Report

Synergies with Power Generation and LCAs

SUMMARY

The project aimed to develop plausible scenarios in Australia for power generation with mineral carbonation (MC) and utilisation of MC by-products. It was to develop high-level process models for industrial scale power generation with MC that incorporates optimised processes developed in the other research and pilot strands.

RESEARCH IMPACT ON TECHNOLOGY DEVELOPMENT

CO_2 Cost Reduction	Scale Success	IP Contribution	Overall Success Score
10%	**50%**	**10%**	**80%**

PROJECT OBJECTIVES AND TECHNICAL OUTCOMES

To demonstrate lifecycle benefits of mineral carbonation in combination with alternative power generation.

Several comprehensive LCAs were completed with carbonation linked to alternative power generation scenarios, demonstrating the life cycle benefits over conventional CCS in several cases.

Consider retrofit scenarios of MC onto conventional coal-fire power generation technology which has an existing carbon capture technology.

Retrofit scenarios for conventional coal power generation with oxyfuel and amine capture were considered.

To develop experimental processes to enhance the rate of mineral dissolution and enhance the yield of carbonated precipitate.

Experimental processes were developed and used to explore a new 2-stage process.

To determine the water consumption efficiency of the most promising power-generation – MC combination.

Water consumption was quantified for all scenarios studied.

The overall goal, on a greenhouse gas lifecycle basis, is to show that the integrated power generation - mineral carbonation process produces fewer emissions than current coal-fired power generation technologies.

On a greenhouse gas lifecycle basis it was shown that integrated power generation-mineral carbonation processes could be comparable to, or better than, geosequestration, provided target conversion efficiencies could be achieved. The new 2-stage process showed the most promise in this regard.

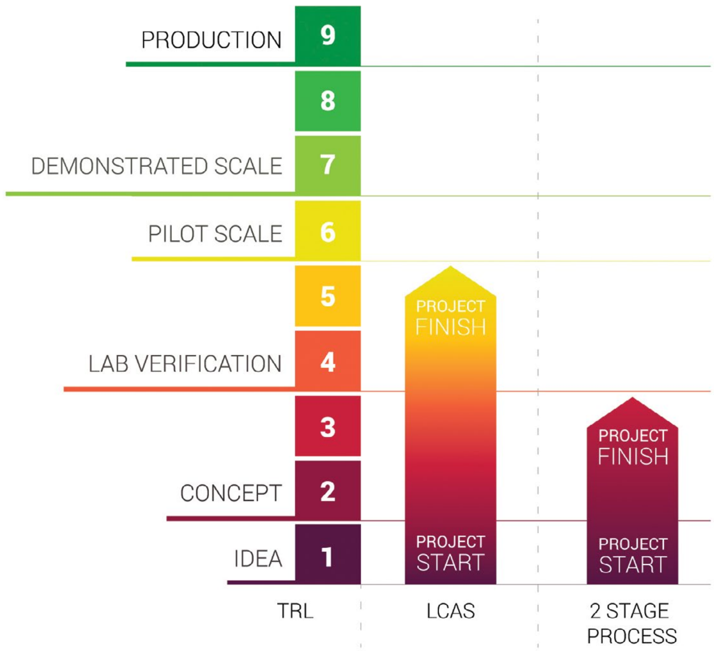
On a by-product basis, the LCA should aim to show that the production of building products from the MC process generates similar or fewer greenhouse gases (or consume less energy) than standard brick production technologies.

This was not specifically studied in this Strand, however work in Strand 2.5.2 showed that using MC product as a cement replacement reduces overall greenhouse gas emissions.

LCA Scenario	Geosequestration (kg CO_2/ MWh_e sent)	2 Stage Mineral Carbonation (kg CO_2/ MWh_e sent)
Conventional coal with amine capture	314	297
Oxy-fuel coal	248	141
Direct Injection Coal Engine	281	168

Table 2: LCA results comparing geosequestration to best cases for two stage mineral carbonation process.

TECHNOLOGY READINESS LEVEL



PROJECT CHALLENGES AND OBTAINING RELIABLE DATA ON CARBON CAPTURE PROCESSES

Developing realistic and plausible future scenarios was challenging, as well.

GAPS

Further optimisation of process conditions are required to maximise Mg extraction

NEXT STEPS

Further R&D by MCi is to be focused on the new 2 stage process, which has shown the most promise for producing value-a ed products and a favourable lifecycle profile.

COMMENTARY

The project was conducted on buţet.

FINANCIAL SUMMARY

Budget item	Budget costs	Actual Expenditure
Income	**$550,000.00**	**$550,000.00**
Management fee	$55,000.00	$54,500.00
Employment costs	$476,000.00	$385,232.00
Equipment	$4,000.00	$17,812.00
Consumables & Analyses	$11,000.00	$83,326.00
Travel and Conferences	$4,000.00	$8,630.00
Total:	**$550,000.00**	**$549,500.00**
		$500.00

Strand 3.1.0 Final Report

Program Governance

SUMMARY

This strand was concerned with the management of the project, the meeting of milestone reporting and the financial coordination for the project. Primary activities included stakeholder management, organising the Funding Committee quarterly meetings, compiling reports, coordinating legal and accounting services and planning of the project. The MCi project governance involved the coordination of agreements between the 5 parties including the three MCi funders and the two other MCi shareholder groups.

ACHIEVEMENT SUMMARY

Quarters Reported	Financial Acquittal	Governance Outcome	Buţet Expended
18	**100%**	**100%**	**A$9.12m**

PROJECT OBJECTIVES

MCi successfully delivered the project through 18 quarters of reporting to its Funding Committee which was represented by Commonwealth & NSW Governments and Orica members. Throughout the project, the members had various changes of staff sitting on the Funding Committee so the continuity of knowleţe and decisions across the project were critical.

Coordinating the research and development reporting of over 30 researchers and engineers on a quarterly basis was a substantial task but was delivered in a comprehensive manner. Most quarterly reports compiled over 150 pages of unique research and development activities which demonstrated the rigour and focus being applied in the MCi Project towards its project goals.

Newcastle Innovation, its successor TUNRA and the University of Newcastle were the responsible research providers for the project and had responsibility for maintaining agreed buţets and coordination of payments and delivering the research program.

PROJECT CHALLENGES

The project encountered various delays as could be expected in a complex scientific and engineering project with many moving parts. The quarterly reporting was necessarily delayed for many of the quarter periods, however the Funding Committee accepted the variances in delays and extension of milestones where appropriate such that the project could continue within the agreed tolerances of time and buţet. No a itional buţet was sought for the project from the original funding agreement.

Final project accounting required some aTustments in buţets since the interface between the University and MCi was not completely transparent with the entities within the University changing throughout the project.

MCi's COO Sophia Hamblin Wang with government funding representitives

GAPS

The interface between research and management is problematic. A research collaboration framework was put in place by MCi and to a limited extent was observed by the research groups. Tighter and specific prescriptive agreements with research teams could have improved the reporting and buţet management issues.

Strand 3.2.0 Final Report

Communications and Media Management

SUMMARY

This activity involved the communication of the project through internal and external stakeholders. Issues including public awareness, media management, communication strategy, technology /solution showcasing, PR, media and web management responsibilities were managed in this Strand. The most significant outcome of this Strand was the garnering of positive sentiment of the public for our technology. In particular, the concept of turning CO_2 into building materials was a breakthrough for MCi in attracting global attention.

ACHIEVEMENT SUMMARY

Media Articles	Speaking Engagements	Awards	Launches
100+	**24***	**1**	**3**
(Incl. New Scientist and The Guardian)		(Berlin 2018)	

PROJECT OBJECTIVES

MCi established a communication strategy and maintained it throughout the project. This included a communication plan which had MCi initiate a public discussion on the technology. It also opened up discussion with industry around the new solution space of carbon storage and utilisation (CCUS) as opposed to CCS.

MCi maintained a media script with its stakeholders which assisted in the positioning of a positive narrative in the media for the project and its aims as a sustainable technology in the climate solution space.

We built and maintained a web presence and social media channels as well as a video explaining the project. A following of public and industry interests and a database of contacts in media and domain influencers was developed.

MCi and this pilot plant project gained global awareness through its media exposure, public unveiling activities and through its climate change technology positioning with the public. It also positioned well within the CCS community and Australian and overseas government interests such as Japan, India, China and Singapore.

**MCi was involved in many speaking engagements including TEDx, BZE Cement Report, Science Meets Business, ICCDU Shanghai, Advanced Carbonation Conference in NY 2015 and hosted in Newcastle 2018, lectures at various climate events, workshops and lectures at universities.*

10 | NewScientist | 2 April 2016

Emissions reveal a constructive side

Richard Schiffman

TAKING carbon dioxide out of the atmosphere is crucial to slowing the progress of climate change. But rather than lock all that CO_2 away underground, what if we could use it to make things? That's the aim of a pilot plant at the University of Newcastle near Sydney, Australia.

Launched last week, the plant will test the commercial potential of mineral carbonation, a process that forms stable materials by chemically binding CO_2 to minerals containing calcium or magnesium. The plant will bind the gas into crushed serpentinite rocks to create magnesium carbonate, which can be used to produce cement, paving stones and plasterboard.

It could be a way of "permanently and safely disposing of CO_2 and making useful products in the process", says Klaus Lackner of Arizona State University in Tempe, who pioneered the technique in the lab.

The process happens naturally when rocks are gradually weathered by exposure to CO_2 in the air. This helped cut the proportion of the gas in the ancient atmosphere to levels low enough for life to flourish, says Geoff Brent, senior scientist at Orica, an explosives manufacturer based in Melbourne. His firm is supplying the plant with CO_2 – a by-product of making ammonium nitrate.

But we can't afford to wait millions of years for geology to rid the atmosphere of our greenhouse emissions. "It's about turning the natural process into a large-scale industrial process on our required timescale – which is extremely urgent," says Brent.

There are several challenges. Mining for serpentinite is energy-intensive and damaging to the environment, for one thing. But Brent says the rock is one of the most common on Earth, and that carbonation plants could be built near mining areas to reduce transport emissions.

Another objection is that mineral carbonation costs too much compared with storing CO_2 underground. However, underground storage has its own problems: suitable repositories are hard to find and there is a risk that the gas may one day escape.

"Carbonation is more secure in the long term, because there is no danger of leakage and no need to maintain long gas pipelines and transportation infrastructure to move the CO_2, since we will be obtaining it on-site," says Brent.

"The whole point of the project is to get the price down low enough," says Marcus Dawe, CEO of Mineral Carbonation International, the firm coordinating the effort. "It is all about how we can make this economical."

Dawe and his team are optimistic that they will make progress by the end of the 18-month pilot project. But for mineral carbonation to take off, there will need to be a higher price on carbon, says Dawe, because right now "nothing is more economical than putting CO_2 in the air". ■

MINERAL CARBONATION INTERNATIONAL

Made with greenhouse gases

New Scientist article following MCi's commissioning of its first reactor in 2016

COO Sophia Hamblin Wang won 1st prize in Berlin at the New Materials Summit 2018. MCi was named Resource Innovator of the Year.

CEO Marcus Dawe speaking at public unveiling of semi-continuous research pilot plan in 2017.

PROJECT CHALLENGES

A limited buţet for these activities and a draw on communication resources into project management meant that not as much time could be spent on further activities and outreach. However this did not substantially affect the interest in MCi.

Strand 3.3.0 Final Report

Commercialisation

SUMMARY

This involved early commercialisation responsibilities such as IP protection, maintaining an IP register, corporate capability development, development of a commercialisation plan (included in the Appendix) and generally identifying market and partnering opportunities. A register of collaboration parties was constantly maintained. MOUs and non-disclosures were negotiated and signed to initiate momentum towards MCi's commercialisation goals.

MCi also researched and monitored relevant policies and programs in Australia and internationally and assisted in lobbying governments on policy to support carbon utilisation. This activity was also assisted by GreenMag Group Pty Ltd, one of the shareholders of MCi.

ACHIEVEMENT SUMMARY

MOUs/NDAs	Potential Projects	Conferences	Visitors to Pilot Plant	Patents/Provs
24	**4**	**14**	**300+**	**6**

PROJECT OBJECTIVES

This strand ran throughout the project timeframe but significantly accelerated in the second half once the economics of our solution started to become evident and the economic feasibility was better understood.

Project IP was largely in the form of know-how of plant design and operability and as such was kept in-house. One patent application reached national phase, a further two are under development. MCi is seeking to license Orica's two international patent families on heat activation of serpentinite.

Early commercialisation activities have been conducted with several partnering opportunities progressed in Australia and in Singapore for private investment and advancement of the technology into future pilot and demonstration projects.

Adopting the TRL methodology for the MCi technology in 2017 allowed it to credibly frame its progress to funders and towards next stage development goals and plans.

MCi's banner representing the project in industry conferences

PROJECT CHALLENGES

Commercialisation is not an exact science and is considered a 'contact sport'. It is important to not overpromise or move too quickly which is the primary challenge in technology development. We believe we have run this line very well in both building our technology credibility and gaining interest. Following this project, MCi is in a superior position to attract funding and investors for demonstration projects and further R&D.

Strand 3 overspend was due to the a itional cost of stewardship of the project and increased IP-related expenses. Accounting, auditing, reporting and reviewing were all allocated to this stream. A itional conferences and communications events for the Strand 1, 2 and 3 staff were paid for under this cost centre. IP costs continued to expand as new breakthroughs were made.

FINANCIAL SUMMARY

Budget item	Budget costs	Actual Expenditure
Income	**$890,000.00**	**$890,000.00**
Management fee	$89,000.00	$83,750.00
Program executive Management Staff salaries	$640,000.00	$656,549.09
Travel & Conferences	$15,000.00	$35,121.59
IP and External Resources	$146,000.00	$337,781.17
Total:	**$890,000.00**	**$1,113,201.85**
		-$223,201.85

Project Description Summaries

01

Scale up the throughput of CO_2 processing from grams per hour in laboratory experiments to kilograms per hour (in batch operation).

The project successfully scaled up the processing of CO_2 from grams per hour in the lab to kilograms per hour in both the batch and semi-continuous pilot plants.

Laboratory experiments employ small autoclave reactors with volumes in the range of 300 to 600 mL, capable of processing up to approximately 30 grams of CO_2 per hour. The pilot scale batch reactor consists of a 30 L volume autoclave reactor, with a CO_2 throughput of approximately 1.5 kg CO_2/hour. During the course of the project, more than 100 laboratory carbonation experiments were conducted and the two pilot plants ran for over 900 hours.

02

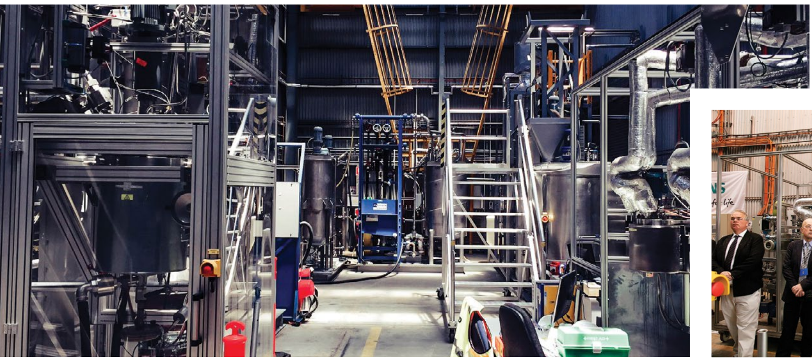
Generate information about the integration, economics and energy requirements of process units to further reduce CO_2 storage costs, in particular, optimising the operating conditions in large scale process unit operations.

A detailed engineering study optimising the process economics and energy requirements was conducted in Strand 1.2.0 for all major unit operations, supported by plant experimental data obtained in Strand 1.1.0.

MILLING

A state of the art High Intensity Grinding mill was installed in the research pilot plant to characterise the milling energy requirements and establish the optimum operating conditions including feed rate, grinding media type and media size. Signature plots were developed to describe the relationship between mill power input and output particle size, enabling the milling energy requirements of a future large-scale plant to be estimated with high accuracy.

The milling circuit was simulated and optimised using JKSimMet software to minimise the cost and energy requirements for a full-scale milling operation. Quotes for full-scale equipment purchase and maintenance were obtained from equipment suppliers enabling capital and operating costs to be estimated with high accuracy.



THERMAL ACTIVATION

An optimised thermal activation process was designed with the objective of minimising the cost of the process, taking into account energy consumption and its effect on the net quantity of CO_2 stored. To minimise energy costs, the heat contained within the activated material is recovered in a series of cyclone coolers, whilst the heat in hot combustion gases is recovered to pre-heat the incoming solids.

Rotary kiln operating conditions including inclination angle, rotation speed, shell temperature and product feed rate were optimised in pilot scale trials, providing sufficient data for future scale-up. New designs were successfully demonstrated at pilot scale. Quotes for full-scale equipment were obtained from equipment suppliers, enabling capital costs to be estimated with high accuracy.

REACTOR INCLUDING HEAT INTEGRATION WITH AMINE CAPTURE

A bubble column reactor was demonstrated in the semi-continuous pilot plant, confirming its suitability and enabling an accurate estimate of capital cost of larger reactors. A concept design for integrating the reactor with the amine capture plant was developed, including a series of heat exchangers that enable heat generated in the carbonation reactor to supply part of the heating requirement to regenerate the amine solvent.

CO_2 COMPRESSION AND SLURRY ENERGY RECOVERY

Concept designs were developed for CO_2 compression and reactor energy recovery and quotes obtained from suppliers. The depressurisation and compression systems were optimised in terms of a trade-off between the number of stages (which impacts capital costs) versus the operating costs and energy requirements.

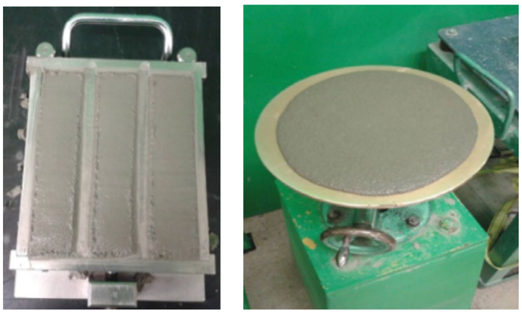
03

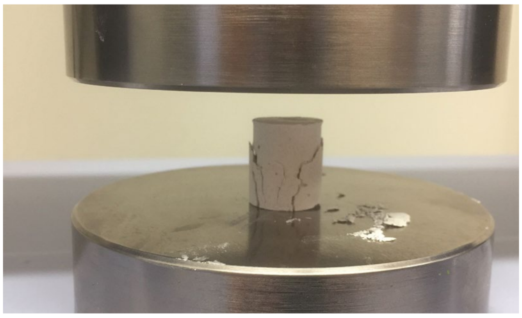
Generate enough product rocks to assess the feasibility of manufacturing useful materials from the process, in particular magnesite silica bricks and pavers.

The batch pilot plant was successfully employed to generate sufficient quantities of product for testing in construction materials. The materials produced were used to prepare cement mortars to assess the suitability of various mineral carbonation products as cement replacements in concrete products, including construction blocks. A range of mineral carbonation by-products were examined, substituting from 5 to 20% of the cement content, including:

- Heat-activated serpentine
- Carbonated product from the ARC process, consisting of a mixture of magnesium carbonate, silica, and unreacted heat-activated material
- Silica enriched residue (SER) prepared in the two-stage carbonation process, at a range of particle sizes
- Acid treated silica enriched residue (ATSER), which is a refined version of the SER product with higher silica content

Cement mortar preparation mould (left) and cement paste flow testing





The results indicated that cement replacement proportions up to 10% are technically feasible for all products, with similar strength to standard cement formulations. All products showed some degree of pozzolanic activity, a strength enhancing reaction that occurs between amorphous silica and components of cement. The pozzolanic activity was highest for ATSER, however, the strength improvement was counteracted by an increase in the amount of water required in the formulation to achieve the desired workability.

The batch plant was also employed to generate sufficient nesquehonite (hydrated magnesium carbonate) for a preliminary assessment of its suitability as a substitute for gypsum in plasterboard. Samples exhibited sufficient compressive strength and exhibited similar physical appearance to conventional plasterboard materials.

05

Make the carbonation process less energy intensive and less expensive to operate.

We identified a number of improvements to the carbonation process to reduce energy consumption and cost, including:

INTEGRATION WITH AMINE CAPTURE

We developed a concept design to capture the heat released during carbonation and employ this to supply some of the energy required by the amine CO_2 capture process.

We also developed concept designs to capture the CO_2 emissions from heat activation in the amine plant, reducing the cost per net tonne of CO_2 stored.

REACTOR DESIGN

We designed, constructed and demonstrated a continuous reactor with no moving parts or dynamic seals, proving that this design can achieve the same yield as a stirred autoclave reactor. This reduces both capital costs by simplifying the reactor design and construction, and reduces operating costs by eliminating the agitator power requirements, maintenance and downtime of a high pressure dynamic seal.

OPTIMISED GRINDING

We successfully operated the high intensity grinding (HIG) mill in our pilot plant, demonstrating a 70% reduction in grinding energy for a product size of 37 microns, relative to the previous best available data from the ARC based on conventional technology. We also optimised the design of the milling circuit to reduce grinding energy requirements.

HEAT ACTIVATION ENERGY EFFICIENCY

We developed optimised designs for thermally activating serpentine to minimise energy requirements and costs. Heat contained in hot combustion gases is recovered to pre-heat the incoming solids.

CO_2 COMPRESSION AND ENERGY RECOVERY

We optimised the process for CO_2 compression, slurry pumping and depressurisation to recover as much energy as possible during slurry depressurisation. Slurry is depressurised in stages, with the CO_2 released from the liquid in the higher-pressure stage requiring less energy to recompress than if depressurised completely to atmospheric pressure. We conducted cost-benefit analyses to demonstrate the economic benefit of employing energy recovery equipment during slurry depressurisation.

TWO-STAGE PROCESS

We developed a new process for mineral carbonation using less extreme process conditions that achieves higher reaction yields of 75% and produces separate carbonate and silica rich product streams. The higher yield reduces the quantity of serpentine required per tonne of CO_2 stored, reducing process costs and energy requirements. The higher purity products can provide a revenue stream that is not available in the conventional ARC process. This makes the new process potentially revenue positive.

MCi Commercialisation

Strand 3.2 of the MCi Project is concerned with Commercialisation. Through the course of the MCi project, the MCi board and its stakeholders have been developing different approaches to commercialising the technology which has emerged from MCi's first four years. This involved issues of strategic direction, commercialisation planning, business model development, competition and funding. While such matters are commercially secret the MCi board provides here a snapshot of planning to provide funders of the project a view on current thinking and progress towards commercialising the MCi technology.

CONTEXT

This Final Report shows how MCi set out to examine the feasibility of mineral carbonation as a means of storing CO_2 from industrial emissions. The project found the US ARC process was not likely to be competitive with other mitigation technologies when tested using Australian feedstock ores.

However MCi developed a new two-stage mineral carbonation technology (the MCi process) which stores CO_2 by transforming captured CO_2 into by-products which can be made into valuable building materials. Research indicates the MCi process at industrial scale could transform a tonne of CO_2 into building material products the sale of which could more then offset the costs of storing the CO_2. There is potential to further improve the MCi process by applying it directly to flue gas emissions so removing the need for carbon capture – this possibility is being examined in the current CRC-P project. Further research and development is required to develop fully the technology and the economics of the MCi process.

MCi Signing MOU in Singapore with technology partner Armourshield Holdings Pte Ltd to explore China and Singapore oportunities

STRATEGIC DIRECTION

MCi needs to grow from an R&D company into a carbon solutions company. The next phase of the project is MCi2.

The key to progressing MCi2 will be a demonstration plant that will operate at small industrial scale and return commercial benefit for its investors.

Assumptions going forward include:

- strategic investors in MCi and governments will fund MCi2 in 2019-2021.
- early adopters of the MCi process in building material markets will pay for construction of demonstration plants in the short term (2020-2025).
- Singapore is the likely first mover for a demonstration plant.
- new materials, regional economics, CO_2 pricing and energy transition dynamics will help attract capital for the scale-up in the medium term (2021-2031).
- Government policies requiring negative carbon emissions and a carbon price will help capital raising for continued deployment in the long term (2030+).

- Governments will engage with the industry development, regional job creation and international co-operation potentials of an emerging carbon utilisation industry.
- Orica will be joined by other major corporations interested in industrial transition to low carbon technologies.

Strategic aspirations include:

- aiming to be a global solution provider for carbon utilisation.
- going to market through channel partnerships, country master licences, joint ventures and licensing/support deals.
- attracting strategic investment from suitable industry partners.
- developing joint regional ventures to take master licenses and build, own and operate plants.
- improving the MCi technology by continuous research and process improvements and buying enabling or blocking IP to boost the platform's value.

COMMERCIALISATION PLANNING

Commercialising the MCi process will require further research and development growing MCi's corporate capabilities; and establishing a demonstration plant at small industrial scale. Brief descriptions of our thinking on each and the costs for each over the next three years are as follow.

RESEARCH & DEVELOPMENT

The MCi process is still at an early stage of development compared with the ARC process. While work to date has identified promising potential there is still more work required to confirm feasibility at industrial scale and to guide commercial implementations.

Much of the work now needed concerns confirming the ability of the MCi process to enable production of green building products, in particular wall sheeting, speciality silicas and in cement. Further work is needed on projected demands for such products and the likely impacts on future markets of large scale transformation of captured CO_2. Similarly further work is needed to establish the feasibility of feedstocks other than serpentinite ores such as fly ash and steel slag.

Experience thus far suggests there will be opportunities both to create new patentable IP around the MCi process and to acquire relevant IP from overseas sources.

The CRC-P project is already examining the possibility of eliminating carbon capture by developing the MCi process to work directly with flue gases. The a itional research and development outlined above would cost around A$9m over three years.

CORPORATE CAPABILITY

MCi to date has been primarily a research company but now will need to also develop corporate capabilities to commercialise the MCi process. It is expected that governments and major corporations will become interested in carbon utilisation in coming years. In that commercial and policy environment MCi will need to maintain its current lead position if it and stakeholders are to benefit. This will require expanded corporate capabilities in operations, marketing, administration; awareness promotion and international co-operation.

Given the assumptions made above, these in-house capabilities are estimated to cost MCi around A$10-$10m over the next three years.

DEMONSTRATION PLANTS

At present the most likely demonstration plant will be in Singapore where Singapore Government agencies are showing real interest in building a scalable oil/gas refining demonstration plant on Jurong Island. There are serious issues involved in a demonstration plant in Singapore, not least of which include the possible loss of industry development opportunities and IP to an overseas early adopter. The US and Australia however could become attractive with policy settings for CO_2 utilisation technology.

Pre-feasibility work involving Singapore's A*Star research agency and potentially Economic Development Board (EDB) is due to start later this year. Singapore is seen as the lead demonstrator for China, Taiwan and Japan where projects are not as far progressed.

An early estimate of the cost to MCi of designing the demonstrator and managing the construction would be around a further A$10m (a itional to the research to be funded by A*Star).

Work to date indicates that in Australia an UltraSuperCritical coal-fired power station could offset the cost of storing emissions by using the MCi process on a proportion of its emissions. Subject to work proposed for MCi2 such a power station might even be able to store carbon profitably, possibly even without a carbon price.

One possibility might be for staged demonstrations in which an Australian project was able to benefit from the Singapore experience. While oil/gas refining and coal-fired power generation are obviously different there will be some commonalties from which will assist later projects.

COMPETITION

MCi has conducted several scans of the mineral carbonation solution space as well as a patent landscape review across the world.

There are now commercial operations using mineral carbonation for small application such as air pollution residue processing in the UK. However these are not direct competitors. The field is however increasing with solutions utilising CO_2 in construction materials and particularly in new cement processes like curing and injection.

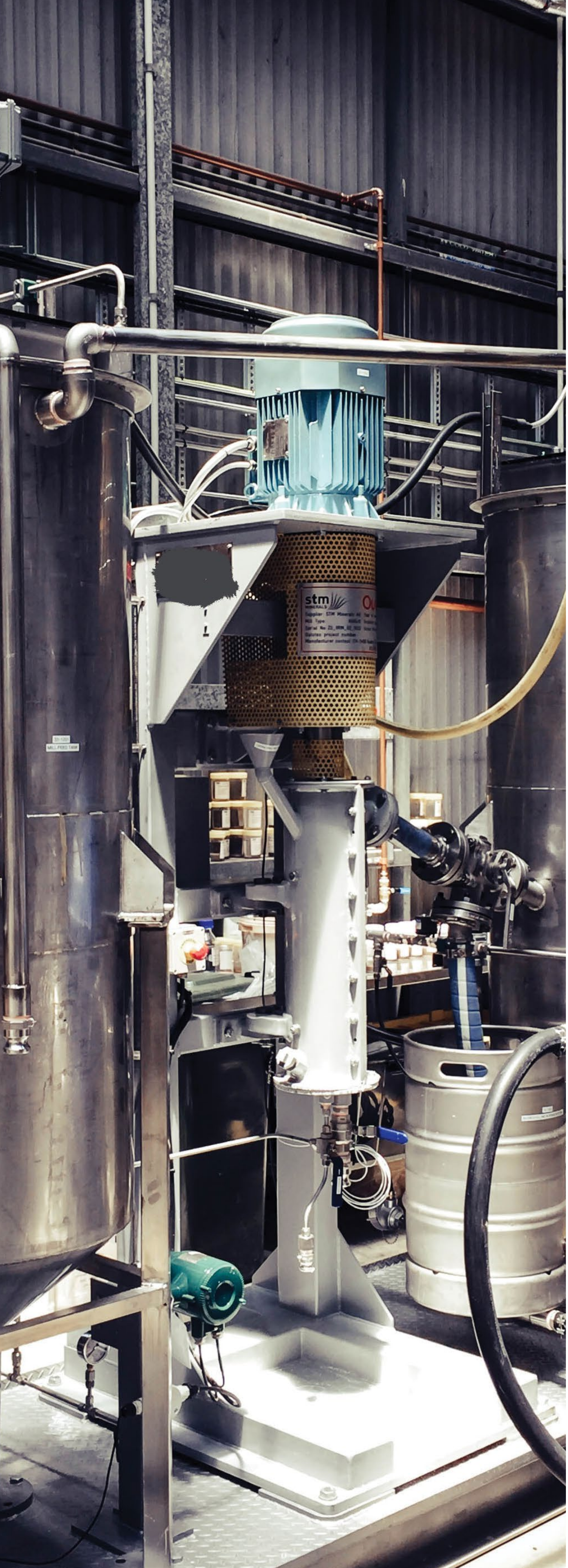
There is potential for competition from China. Chinese companies have shown interest in what MCi is doing but as yet we have not identified any similar operations coming out of China.

MARKET RESEARCH

MCi has started a complete market review in building materials manufacturing where mineral carbonation by-products could provide raw materials. Our economic research is identifying those sectors which are attractive as targets for partnerships. Some headlines of our findings:

- Global construction material market (concrete and building materials) is growing at a CAGR of 6.76% during the period 2017-2021.
- China's demand for Cement & Concrete is A itives growing at about 6% pa until 2027
- The Global Cement market size was valued at USD 355.6 billion in 2016. It is expected to register a CAGR of 7.8% from 2017 to 2025.
- Source: http://www.sbwire.com/press-releases/cement-market-growing-trends-demand-in-construction-sector-2019-to-2025-1174624.htm
- Global construction aggregates market to grow at a CAGR of 6.33% during the period 2018-2022
- Global green cement market to grow at a CAGR of 14.95% during the period 2016-2020
- Global fly ash market to grow at a CAGR of 7.03% during the period 2017-2021
- Plasterboard market size is projected to grow at a CAGR of 5.7% globally during the period of 2016-2021 and reach USD 23.85 billion by 2021.

Of particular interest to MCi is the Asia-Pacific region which is projected to register the highest CAGR globally for plasterboard, between 2016 and 2021. China was the largest market for plasterboard in the Asia-Pacific region, in 2015. The Chinese market is projected to grow at the highest CAGR during this period. The growth of construction activities in the region as well as population in China, Indonesia, and India are driving the growth of the Asia-Pacific plasterboard market.



ONGOING FUNDING / CAPITAL RAISE

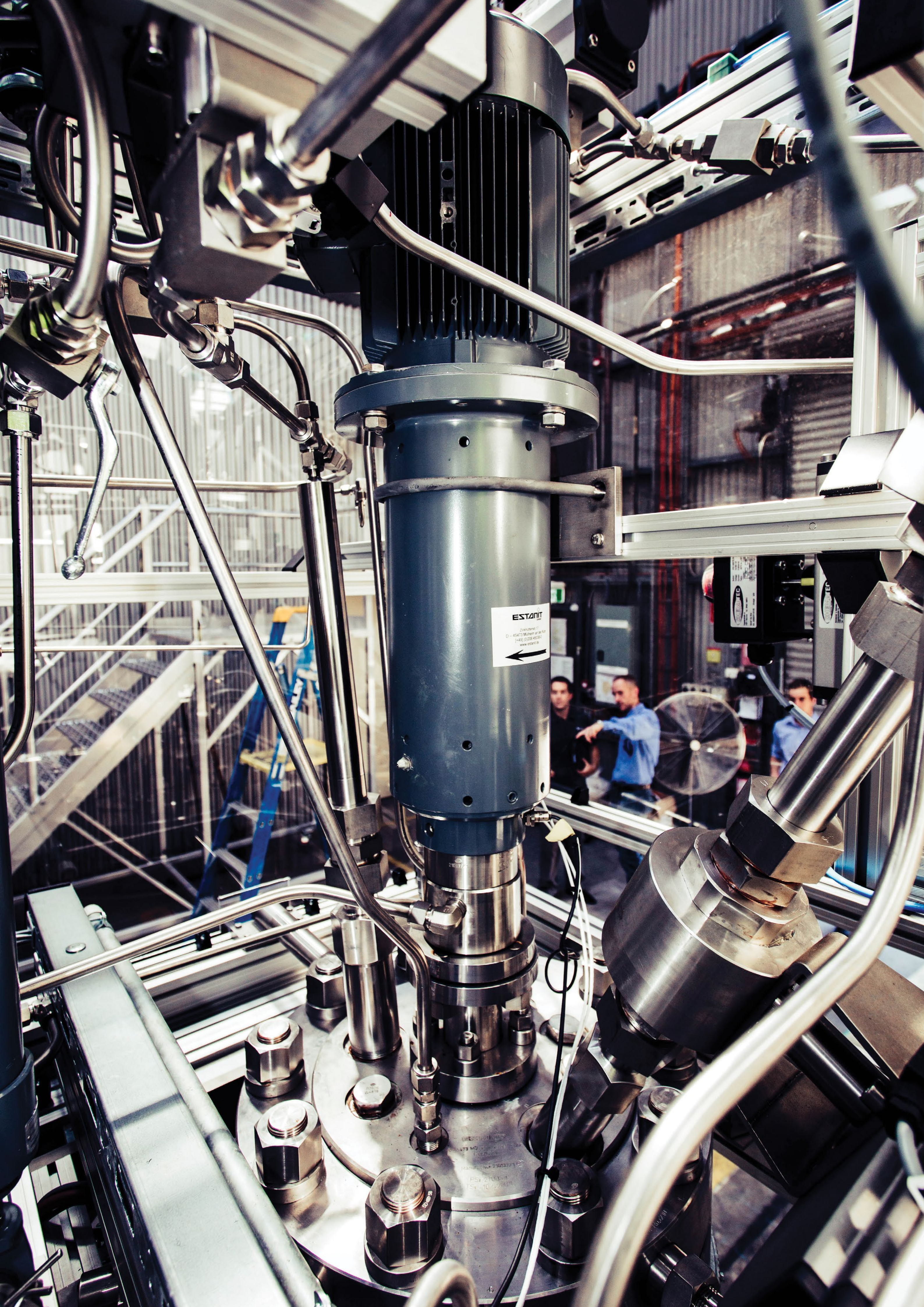
MCi has begun the CRC-P project which will run for three years. Ideally, commercialisation should run in parallel.

MCi is proceeding to raise capital later in 2019 to position it for a larger capital raise to match possible continued government grant support.


FLSmidth
KREBS

MCi PhDs

List of PhDs Supported by MCi	Project	Completion Date
Leo Anderberg	Project 2.1.0	Expected June 2019
Emad Benhelal	Project 2.2.2	Completed 18 July 2018
Muhammad Imran Rashid	Project 2.2.2	Under review, awaiting feedback from examiners
Guanhe Rim	Project 2.3.1	Expected first half 2019
Chengchuan Zhou	Project 2.3.1	Expected first half 2019
Ammar Abu Fara	Project 2.5.2	Completed 22 February 2019
Joshua Lee	Project 2.5.3	Withdrawn
Timothy Oliver	Project 2.5.3	Completed 3 February 2017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