

## Long-Term Storage of CO<sub>2</sub> as Magnesium Carbonate in Finland

**Ron Zevenhoven and Sebastian Teir**

Helsinki University of Technology

Laboratory for Energy Engineering and Environmental Protection

PO Box 4400, FIN-02015 Espoo, Finland

ron.zevenhoven@hut.fi, sebastian.teir@hut.fi, <http://eny.hut.fi>

### Abstract

Since mid-2000 our laboratory has investigated the option of storing CO<sub>2</sub> in the form of thermodynamically stable and environmentally inert magnesium carbonate. Finland has access to vast amounts of serpentine and serpentinite minerals, often found as tailings from mineral or metal processing industries. The objective of our work is to optimize the possibility of magnesium oxide-based mineral carbonation for CO<sub>2</sub> long-term storage in Finland, aiming at improving the kinetics and energy efficiency of large-scale carbonation processing. One specific feature is that we aim at direct, dry carbonation which involves only gas/solid chemistry, operating at temperatures and pressures where the process has a zero or negative energy input requirement.

Tests were made with magnesium hydroxide (Mg(OH)<sub>2</sub>) in a pressurized thermobalance, with humid CO<sub>2</sub>, from 1 to 35 bar pressure. The results show that increased pressure levels don't give the expected increase in magnesium oxide (MgO) carbonation rate. In addition, tests with Mg(OH)<sub>2</sub> and MgO in an atmospheric bubbling fluidized bed batch reactor was conducted. One interesting result was that attrition, abrasion etc. continuously remove small amounts of material from the particles' surface. These fine particles, which are entrained from the reactor, show higher levels of carbonation than (larger) particles sampled from the bed. Experiments in a pressurized reactor set-up will follow. For total system optimization, process simulations are made using Aspen Plus.

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### Emissions and long-term storage of CO<sub>2</sub> in Finland, and the mineral carbonation option

As an EU member state, Finland is committed to the 1997 Kyoto Protocol, which means reducing greenhouse emissions to the level of 1990. The target set for Finland appears to be quite challenging since the production and utilization of power and heat is already remarkably efficient. The base industry in Finland is very energy-intensive, and the economical growth has a tendency to lead to an increase in greenhouse gas emissions. Finnish CO<sub>2</sub> emissions were around 70 Mt in year 2003 [1] against 54 Mt in year 1990. Figure 1 shows the locations of large CO<sub>2</sub> emitters in Finland [2].

The primary options for CO<sub>2</sub> disposal are underground storage, ocean sequestration, and storing CO<sub>2</sub> as inert solids. Assessments have shown that many of these options are relatively cheap compared with the cost of capturing the CO<sub>2</sub> in the first place. Significant uncertainties, however, are involved in most of the

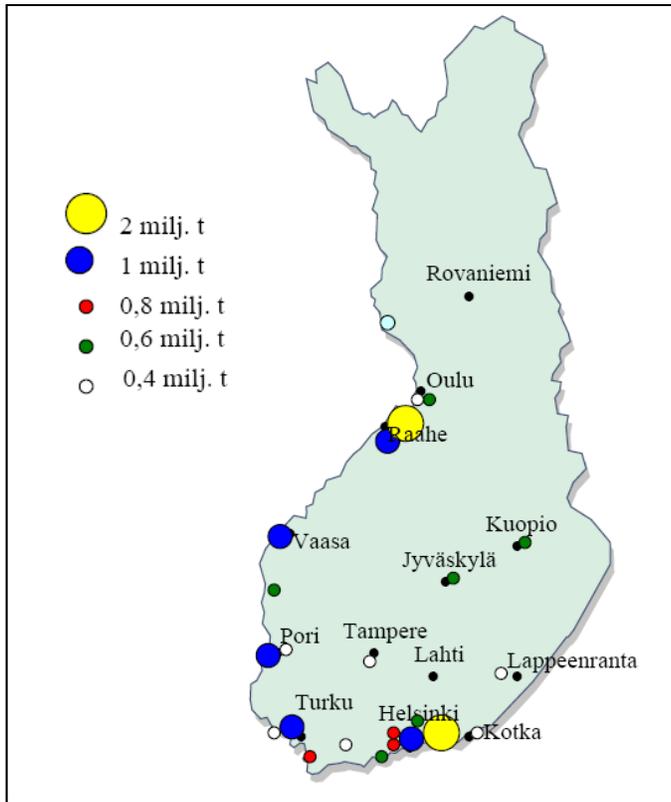


Figure 1: Large CO<sub>2</sub> emissions sources in Finland [2].

schemes, indicating the need for further research and development. Long-term storage of CO<sub>2</sub> could be accomplished by mineral carbonation if the rate of the carbonation reaction can be increased. Mineral carbonation appears to be the best, if not the only, option within Finland's borders for solving the CO<sub>2</sub> sequestration problem [3].

Finland has widespread deposits of the mineral needed in the carbonation process. In addition to the conversion process itself, several other questions regarding the mineral extraction processes and the disposal and use of the end products must be solved in order for the process to function on a large scale. One problem is that in Finland most CO<sub>2</sub> sources are not located near the mineral producing mines. This means that a transportation system for CO<sub>2</sub> would have to be designed. Transportation of minerals has been proven to be prohibitively expensive and is thus out of the question.

### Mineral carbonation in Finland

Long-term storage of CO<sub>2</sub> may be achieved by mineral carbonation, which is the process of converting CO<sub>2</sub> using naturally occurring minerals such as magnesium- and calcium-based silicates into permanent carbonate minerals. Equation 1 shows the net reaction of the carbonation process of magnesium silicates:



Thermodynamics puts restraints on the stability of MgCO<sub>3</sub>: at CO<sub>2</sub> pressures of 1 bar (14.7 psi) MgCO<sub>3</sub> is stable up to temperatures of around 400°C (752°F); at 35 bar (515 psi) MgCO<sub>3</sub> is stable up to around 550°C (1022°F).

Resources of magnesium silicates exceed those of the fossil carbon by several orders of magnitude [4, 5]. Using mineral carbonation to reduce CO<sub>2</sub> emissions has several advantages such as long-term stability, and offers vast storage capacities for CO<sub>2</sub>. In Finland mineral carbonation of CO<sub>2</sub> appears to be the only domestically available option for long-term storage of CO<sub>2</sub>. Disadvantages of the process are a possible asbestos content of the minerals involved, and the large mass flows of solids involved. Still, neither the size of the plant to sequester, say, the 3 Mt CO<sub>2</sub>/year produced by a modern coal-fired power station with a capacity of 500 MWe, nor the environmental implications are considered to be a problem [6], although the vast amount of solid products to be disposed of will not remain without consequences to the environment.

There are two main problems that need to be solved in order for mineral carbonation to be a feasible long-term storage option on a large scale: reaction kinetics must be improved, while the net energy requirements of the process must be minimized. One option for speeding up the reaction is to extract the reactive component, e.g. magnesium hydroxide ( $\text{Mg}(\text{OH})_2$ ) or magnesium oxide ( $\text{MgO}$ ), from the mineral prior to the carbonation. Currently existing processes suffer from either a very large energy requirement, slow reaction kinetics, or both [6, 7]. The mineral extraction processes and the disposal/utilization of the end-products are other questions that must be solved. In addition to the amount and quality of minerals, also the location of minerals with respect to the  $\text{CO}_2$  sources is a key factor. In Finland most  $\text{CO}_2$  sources are located far from the mineral producing mines. Therefore, either  $\text{CO}_2$  or the mineral (or both) has to be transported to the carbonation facility. A  $\text{CO}_2$  pipeline network for  $\text{CO}_2$  transport would be needed.

Magnesium carbonate ( $\text{MgCO}_3$ ) is an environmentally stable and non-toxic mineral. It can be utilized or disposed of as such, since it is not listed as a hazardous waste. Magnesium carbonates are used as construction material, fillers for paper, plastics and rubber, and as thickening agents for printing inks. Pharmaceutical-grade magnesium carbonate is also used in toothpaste and as an antacid, and high-purity magnesium carbonate is employed in cosmetics. Raw magnesium carbonate is used for surface coatings, landscaping, ceramics, and as a fire retardant.

Magnesium silicates can be found as a base component in ores mined for metals such as nickel and gold. In Finland mining activities exist at several locations: the most important metals that are mined for are nickel and copper, but some mining for talc and limestone also exists. Magnesium-based minerals are already produced as a side product at several mines but increased mining would be required. A mapping of magnesium oxide rich deposits indicates that the eastern and northern parts of Finland have widespread deposits of ultramafic rocks. Examples are the Hitura (nickel) mine and the deposit at Lahnaslampi and surroundings, in central-western Finland.

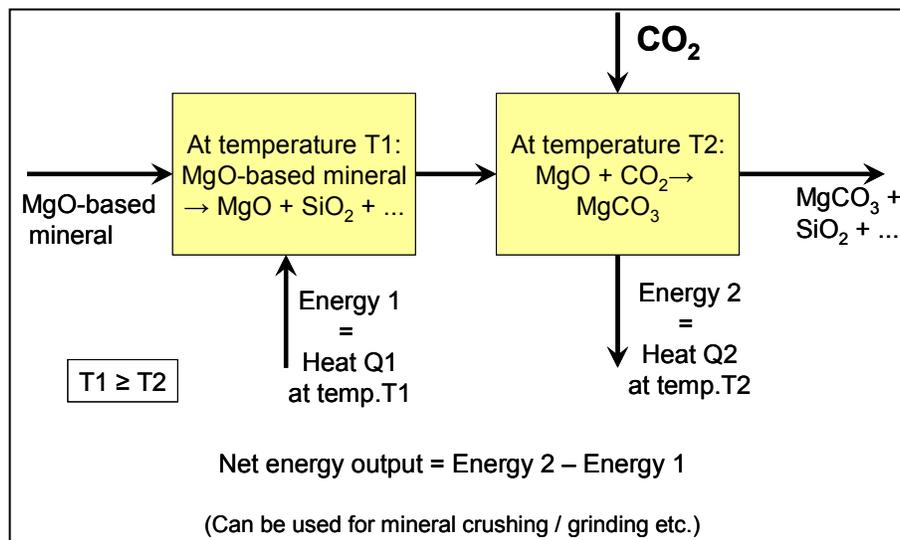


Figure 2: A process for two-stage mineral carbonation.

Extraction of the reactive component from a mineral is very energy intensive; high temperatures are required to separate  $\text{MgO}$  as such or as  $\text{Mg}(\text{OH})_2$  from serpentine. The energy for this should be recovered from the carbonation step, which may yield 600 -1200 kJ/kg  $\text{MgCO}_3$  produced – an impression of such a two-stage process is shown in Figure 2. A recently made exergy analysis shows that the minimum degree of conversion of the  $\text{MgO}$ -content to  $\text{MgCO}_3$  at which the overall carbonation process will have zero or negative net energy input is lower for serpentine (around 85-90% conversion) than for olivine (close to 100% conversion), depending on process temperatures and pressures [8]. Since mining activities do not produce any utilizable waste heat, concentration of the processes involved near each other would be the best option for optimizing the energy efficiency.

The biggest obstacles for applying CO<sub>2</sub> separation and capture technologies are, in addition to the issues related to storage and utilization, the high capital and operating costs and reduced efficiencies. The costs of storage and transportation of compressed CO<sub>2</sub> are expected to be less than 30% of total costs of capture, storage and transportation with current technologies. In Finland's case, however, the transportation distances are fairly long and thus CO<sub>2</sub> transmission costs would be relatively high. Serpentine is a by-product of mining that has no value for the industry. If mineral carbonation can be applied on a large scale serpentine will most likely receive a price tag, thus increasing the storage costs. The cost of CO<sub>2</sub> capture and storage for new fossil fuel fired 500 MWe-scale power plants with current technologies is about 40-60 US\$ per ton of CO<sub>2</sub> emissions avoided [9]. In order for mineral carbonation to be competitive, the price should be below 20 US\$ per ton of avoided CO<sub>2</sub>.

### **Theoretical studies**

Ongoing theoretical work involves mapping of CO<sub>2</sub> producers, mineral resources and quality, and source-sink mapping. Besides the typical sectors such as the heat and power industry, metals, minerals and cement processing also pulp and paper industry, responsible for around 15 % of Finnish fossil-fuel derived CO<sub>2</sub> emissions, is being taken into account [10]. For more detailed on the locations, sizes and quality of mineral resources cooperation with the Geological Survey of Finland (at Kuopio) has started as of year 2004, addressing also the utilization of the products of mineral carbonation.

For the thermodynamic modeling of processes such as shown in Figure 2, process modeling software Aspen Plus® was purchased. This will also allow for simulating cases where mineral carbonation might be integrated with an existing process for the purpose of heat or chemicals integration.

### **Experimental work 1: Pressurised thermogravimetric analysis studies on carbonation reaction kinetics**

As a continuation of earlier tests [11, 12], a fine powdered brucite, Mg(OH)<sub>2</sub>, sample (particle size ~20 μm) was carbonated in a vertical pressurized thermogravimetric analyzer (PTGA) with 16 mm reactor tube diameter. The sample had a purity of 99.7 %-wt Mg(OH)<sub>2</sub>, plus 0.3 %-wt others, which were not further analyzed. Solid sample masses, contained by a cylindrical sample holder (diameter 10 mm, center stem 8 mm., leaving 1 mm for the sample layer) were of the order of 300 mg. Maximum controllable heating/cooling rates in this device were 50°C/min (27.8 °F/min).

With the aim to obtain information on the effect of total gas pressure on direct dry (i.e. gas/solid) carbonation of MgO (periclase), five experiments were made at 1, 5, 12, 20 and 35 bar (14.7, 73.5, 176.4, 294 and 514.5 psi) pressure, all other parameters being the same. Sample size was around 280 mg. The tests involved heat-up -for calcining the Mg(OH)<sub>2</sub> to MgO- to 700°C (1292 °F) at 10°C/min, holding time at 700°C 30 minutes, cooling to 250°C (482°F) at 5°C/min, holding 250°C for 30 minutes and stop. The gas contained 99%-vol CO<sub>2</sub> + 1 %-vol H<sub>2</sub>O. After the tests the samples were sent for chemical analysis, i.e. the Mg and CO<sub>3</sub> (carbon bound as carbonate) content. Figure 3 gives the results from the calcination and carbonation tests at 1, 12 and 35 bar (14.7, 176.4, and 514.5 psi), respectively.

The calcination stage data show that calcination to MgO is completed at 700°C for all experiments, although at high pressures some absorption/adsorption occurs around 450-500°C (842-932°F). The carbonation stages show that at 1 bar a mass increase occurs over the whole trajectory, also where MgCO<sub>3</sub> is not thermodynamically stable ( $T \gg 400\text{ }^{\circ}\text{C} / 752^{\circ}\text{F}$ ). Apparently ab-/ad-sorption of CO<sub>2</sub> or water takes place at the higher temperatures (increasing with decreasing temperature). This is no longer the case at 12 bar where only below 400°C a mass increase is seen, which could be carbonation. At 35 bar the sample

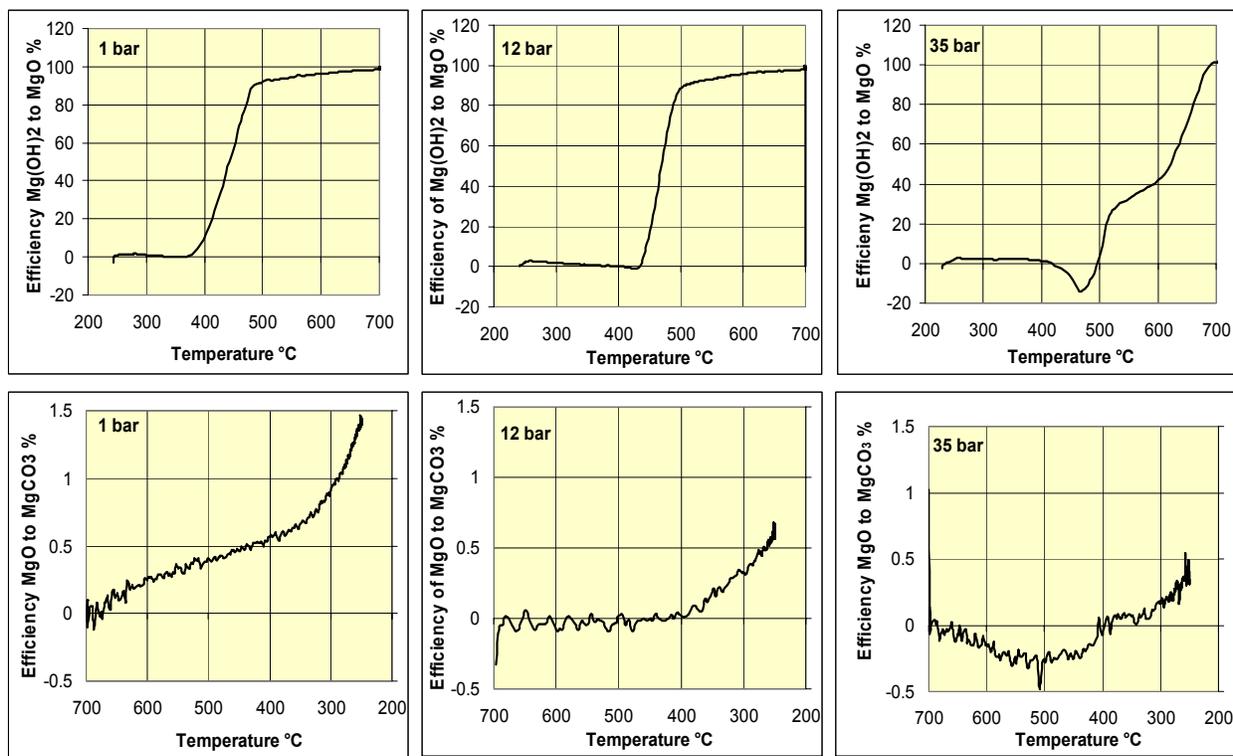


Figure 3: Calcination of  $\text{Mg}(\text{OH})_2$  at 10 K/min (top) followed after 30 minutes by carbonation of the  $\text{MgO}$  at 5 K/min (bottom), in  $\text{CO}_2/\text{H}_2\text{O}$  99/1 vol/vol at 1 bar, 12 bar and 35 bar

weight even decreases while cooling from 700-500°C (1292-932°F), followed by an increasing sample weight upon further cooling. This behavior at temperatures where  $\text{MgCO}_3$  cannot be stable cannot be explained at this point.

One clear trend can be seen that suggests that increased pressure levels reduce the degree of  $\text{MgO}$  carbonation that is obtained. This is contrary to what might be expected from the fact that the reaction  $\text{MgO} + \text{CO}_2 \rightarrow \text{MgCO}_3$  is thermodynamically limited by a minimum  $\text{CO}_2$  partial pressure.  $\text{MgCO}_3$  is stable at higher temperatures under higher  $\text{CO}_2$  partial pressures, and chemical reaction kinetics are usually speeded up by increasing temperatures. Apparently the carbonation of  $\text{MgO}$  with  $\text{CO}_2$  in the presence of small amounts of  $\text{H}_2\text{O}$  does not follow this general trend.

One feature that must be studied further is that a wet chemical analysis of the carbonate content of the samples after the tests gives degrees of conversion that are much higher than shown in Figure 3: these analyses give 5.6 %, 3.1 % and 2.9 % conversion, respectively, for 1 bar, 12 bar and 35 bar (14.7, 176.4, and 514.5 psi).

The scarce literature on  $\text{MgO}$  carbonation consists of only a handful of peer-reviewed articles [13-15]. Nonetheless, a detailed study was recently published on the effect of pressure on  $\text{Mg}(\text{OH})_2$  carbonation [13], studying how hydroxylation (water release) and re-hydroxylation (uptake of water to form hydroxide again) influence and interact with carbonation. That study reports a rapid carbonation to ~2% of an  $\text{MgO}$  sample at 1 bar, 375°C (14.7 psi, 707 °F) after which no further carbonation occurred. Somewhat surprisingly, above the minimum  $\text{CO}_2$  pressure for  $\text{MgO}$  carbonation, both the dehydroxylation reactivity of the  $\text{Mg}(\text{OH})_2$  and the carbonation reactivity of the  $\text{MgO}$  appeared to decrease. A possible explanation is that increasing pressures slow down the dehydroxylation of the  $\text{Mg}(\text{OH})_2$ , thus generating a smaller number of reactive  $\text{MgO}$  sites for carbonation.

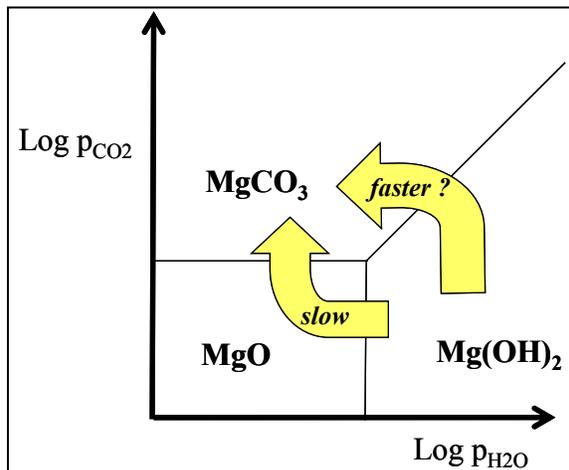


Figure 4: Phase diagram showing stability of  $\text{MgCO}_3$ ,  $\text{MgO}$  and  $\text{Mg(OH)}_2$  versus partial pressures of  $\text{H}_2\text{O}$  and  $\text{CO}_2$ .

In our tests, the temperature was increased to  $700\text{ }^\circ\text{C}$  ( $1292\text{ }^\circ\text{F}$ ) to complete  $\text{Mg(OH)}_2$  calcination, and the PTGA curves shown below confirm that this calcination was complete. Earlier, it was noted that “the presence of water is needed to provide reasonable carbonation kinetics” [14]. It may be that with moisture in the gas, a dehydroxylation/carbonation/rehydroxylation cycle takes place. With a dry  $\text{CO}_2$  gas, the brucite ( $\text{Mg(OH)}_2$ ) is covered by adsorbed  $\text{CO}_2$  molecules, determined by a sorption/desorption equilibrium, causing a much slower dehydroxylation of the brucite, which then gives a more reactive periclase ( $\text{MgO}$ ) for carbonation. Yet more recent work on dolomite calcination [16,17] mentions that the presence of water in surrounding gases enhances the sintering of  $\text{MgO}$ .

Our future tests will involve attempts to carbonate  $\text{Mg(OH)}_2$ , under conditions where the formation of  $\text{MgO}$  is avoided, as illustrated in the phase diagram Figure 4. Thereafter we intend to proceed experimenting with serpentinites and serpentine.

## Experimental work 2: Carbonation experiments in a fluidized bed reactor (at atmospheric pressure)

The direct dry carbonation reaction with  $\text{Mg(OH)}_2$  proceeds very slowly at atmospheric conditions, partly because the reaction causes a layer of magnesium carbonate,  $\text{MgCO}_3$ , to build up on the surface of the mineral particles [13, 14]. This apparent non-porous layer prevents further carbonation of the particle by hindering  $\text{CO}_2$  from penetrating into the particle and preventing water from being released. In order to speed up the reaction rate of dry direct carbonation, Lackner suggested the utilization of a fluidized bed reactor already in 1995 [18]. Fluidized bed reactors are generally regarded as suitable process reactors for gas-solid non-catalytic reactions. The effects of the rapid motion of the bed particles are not only a good heat transfer and temperature uniformity, but also continuous attrition of the bed particles due to collisions. These collisions could possibly break the  $\text{MgCO}_3$  layer on the particle surfaces and continuously enable fresh areas of the mineral to be carbonated. Thus, higher conversion levels and faster kinetics could possibly be achieved by using fluidized bed reactors instead of fixed or moving bed reactors. Comparing different gas/solid reactor alternatives [10] the fluidized bed reactor offers the best heat transfer, good mixing, a wide range of sizes of reactions and a suitable range of particle sizes (from coarse powder to small grains).

The experiments described below were conducted in an atmospheric fluidized bed reactor rig that was available at the laboratory. The main purpose of the experiments was to determine the suitability of (atmospheric) fluidized bed reactors for mineral carbonation and obtain valuable experience before proceeding with experiments with a pressurized reactor. The  $\text{Mg(OH)}_2$  used in the experiments was provided and manufactured by Dead Sea Periclase Ltd. (Israel). The  $\text{Mg(OH)}_2$  content of the material was 97.2 %-wt, a carbonate analysis we had made revealed a carbonate content of 3.65%-wt in the sample. 95% of the particles were in the size range 0.15-0.71 mm.

Three experiments were carried out using the magnesium hydroxide in October – December 2003 with the experiment rig drawn in Figure 5. The facility was primarily designed and used for research on solid

waste treatment. The part of the experiment rig that was used consisted of a bubbling fluidized bed reactor (BFB), a blower (B) for achieving the circulation of the gas and the fluidization of the bed, a tubular heat exchanger (C) for cooling the gas and condensing moisture in the gas stream, and water separators (WS1 and WS2) for removing the condensed water from the system. The reactor worked only at around atmospheric pressure level and the maximum temperature achievable was approximately 500°C (932°F). Specific details about the BFB reactor are presented in Table 1. The temperature inside the reactor was adjusted and regulated with an external electrical heater.

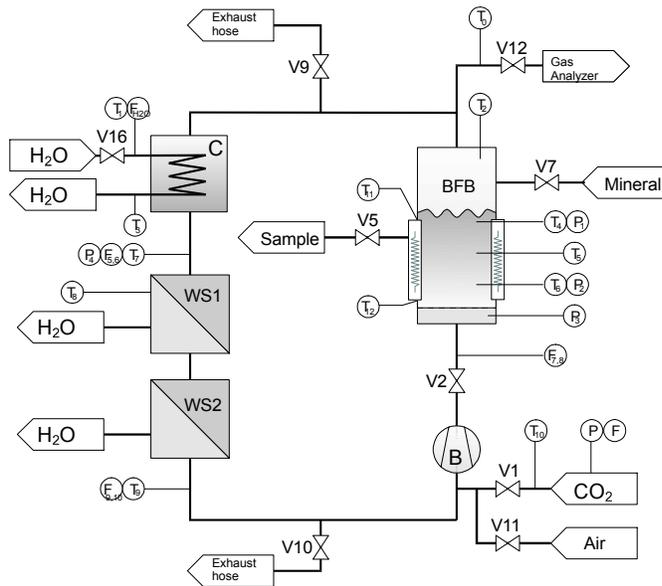


Table 1. Fluidized bed reactor data.

Diameter [m]	0.4
Height [m]	0.8
Distributor type	perforated plate
Number of orifices	190
Diameter of orifices [mm]	3
Bed material (sand) size [mm]	0.13-0.71 (97%)

Figure 5: The atmospheric bubbling fluidized bed test rig.

The pressure inside the process was maintained slightly above the atmospheric level (1.0-1.3 bar, 14.7-19.1 psi) by regulating the CO<sub>2</sub> feed. The fluidizing gas stream consisted of pure CO<sub>2</sub> supplied from gas bottles (purity > 99.5%). During the experiments, 5 l/min of CO<sub>2</sub> left the reactor through a FT-IR gas analyzer. This loss was compensated for by fresh gas feed from the gas bottles. The concentration of CO<sub>2</sub> in the reactor was 90-96% and the moisture content was 4-6% during the experiments, since the water separators were not efficient enough. The CO<sub>2</sub> gas from the reactor exhaust was recycled back to the reactor, in order to meet the reactor requirements of 200-600 liters CO<sub>2</sub> per minute for achieving the bubbling fluidization velocity. Before entering the reactor, the temperature of CO<sub>2</sub> was approximately 25°C. Three temperature probes were placed inside the reactor at various heights in the bed plus one in the void space above the bed inside the reactor. Temperature probes were also situated outside the reactor at various places in the rig to assist the manual control of the process. Pressure probes measured gas pressures and velocities. All probe data was collected by data loggers, plotted on a computer screen in real-time, and stored for analysis. The data from the gas analyzer was logged in a separate computer and analyzed in real-time.

The counting of experiment time started when the mineral batch was fed into the reactor. Samples of the material inside the reactor could be extracted through an overflow outlet on the side of the reactor. In order for the bed material to reach the sampling outlet, a bed height of approximately 0.4 m had to be maintained. Due to the requirement of large volumes of bed material, the mineral was mixed with inert sand at a 1:10 mass ratio. The mass of the mineral batch fed was 7.2 kg. After running the reactor with the mineral inside for a certain time, a final sample was taken followed by cooling and atmosphere

replacement. The CO<sub>2</sub> atmosphere was replaced by pumping air into the reactor (marked in figures with a grey vertical line). This procedure took 20-45 minutes. Cooling was initiated at the same time by shutting down heater elements. After the atmosphere had been replaced (CO<sub>2</sub> content <1%), the pump was shut down and the reactor slowly cooled down by natural convection with air. After the reactor bed had cooled down to approximately 100°C, the reactor was disassembled and a final sample of the bed material was taken. Selected bed material samples were analyzed at an external laboratory. Methods used were AAS, sample fusion and acid digestion, modified ASTM method and CO<sub>3</sub> internal method, and acid digestion + GC. The samples contained sand and small white particles, which were screened out of the sand prior to the analysis. Analysis for Mg and CO<sub>3</sub> was performed on the white particles.

Three experiment runs were made using magnesium hydroxide with varying residence time, bed temperatures, and bed temperature when feeding the mineral. A summary of the differences between the runs is presented in Table 2. Run A1 was performed at a set temperature, run A2 was heated initially beyond the feasible range (as to calcine the Mg(OH)<sub>2</sub> to MgO), and the carbonation of a slow heat-up was tested in run A4. Selected samples of the bed material were analyzed. The temperature variations are shown in Figure 6, Figure 7, and Figure 8, with the carbonation content of the samples plotted at corresponding time for sampling. Note: the first sample analysis on the conversion lines (at 0:00) is the analysis result of the magnesium hydroxide before the experiment (= 4.12 %wt MgCO<sub>3</sub>).

Table 2. Settings fluidized bed carbonation experiments with magnesium hydroxide.

Run	Residence time in CO <sub>2</sub> [h:mm]	Entry temperature [°C / °F]	Cooling time in air [h]
A1	4:01	335 / 637	16
A2	11:12	227 / 441	12
A4	10:47	27 / 81	12

In order to give a faster fluidization, the gas flow of run A4 was varied between 500 – 1000 l/min. At 2:22 there was a pump failure, which caused a pause in the heat-up of the reactor until 3:40. Due to problems with the heater, which occurred after 8 h, the temperature level had to be manually regulated at 350°C. This was the cause for the temperature fluctuations seen in Figure 8.

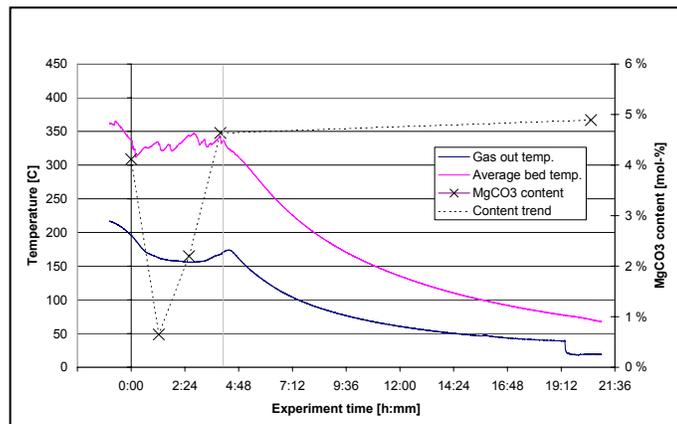


Figure 6: Reactor temperatures and solid MgCO<sub>3</sub> content during experiment run A1.

Temperature variations resulting from the carbonation/dehydroxylation could not be observed. When the mineral was inserted there was an immediate rise in the moisture content of the reactor to 10% in run A1

and A2, which settled after one hour to 4-6%. No particular point for moisture release could be observed during run A4. The Run A1 and A2 suffered from large temperature differences (100-150°C) inside the bed. This was a result from a poor performance of the gas distributor that was fixed before run A4, where the mixing performance was then very good (temperature differences of 1-2°C).

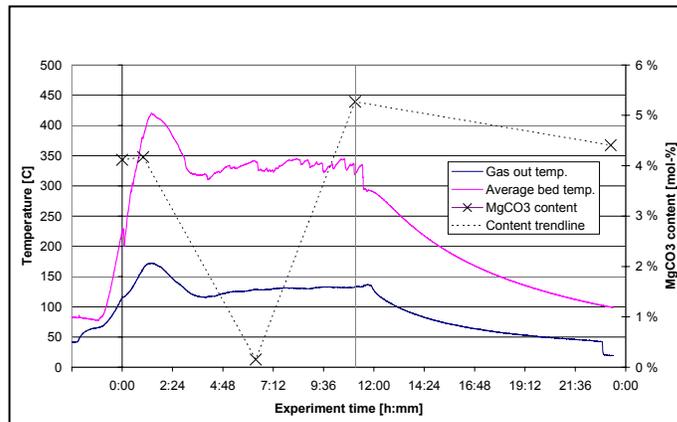


Figure 7: Reactor temperatures and solid  $\text{MgCO}_3$  content during experiment run A2.

The sample analyses of run A1 and A2 show a drop in carbonate content during the first hours. Since the highest local reactor temperatures exceeded the upper limit for a thermodynamically feasible carbonation in run A2, the magnesium carbonates in the magnesium hydroxide were decomposed to almost zero (0.15 %-wt). The external heater elements made the internal wall temperatures higher than the bed temperature, which could have caused the decomposition noted in run A1 and A2. The mineral in run A2 is carbonated slower than in experiment A1. This could be an indication of reduced reactivity of magnesium oxide calcined from magnesium carbonate in comparison with magnesium hydroxide.

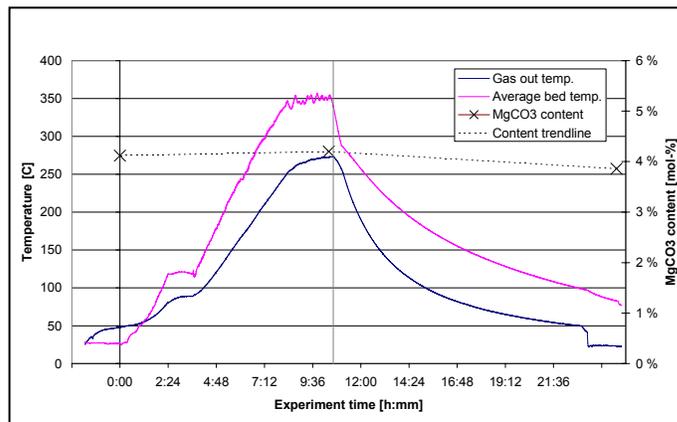


Figure 8: Reactor temperatures and solid  $\text{MgCO}_3$  content during experiment run A4.

Final samples were taken at room temperature, after the reactor had cooled, after run A2 and after run A4. These samples consist of fine powder that had accumulated in the heat exchanger (Figure 5, C) during each experiment, and is therefore not plotted in the graphs. It was analyzed without any preliminary treatment. The particle size of the sample after run A2 was much finer than the average bed material and the considerably higher  $\text{MgCO}_3$  content of this sample (8.1 %-wt versus 4.4 %-wt in the material from the bed) is most probably a direct result from its smaller particle size. Apparently this material is produced from the outer layers of the particles by attrition, abrasion etc. The content of carbonate in the similar

sample after run A4 was not higher, however (4.2 %-wt versus 3.9 %-wt in the material from the bed). The bed material sample after from experiment run A4 was sieved before analysis. Most of the bed material with a diameter below 74  $\mu\text{m}$  had been entrained from the bed. Therefore, the bed material accumulated in the heat exchanger was analyzed for comparison. The results do not show any notable size dependency of the carbonate contents: these were in the range 3.7 – 3.9 %-wt for sizes > 74  $\mu\text{m}$ , against 4.2 %-wt for sizes < 74  $\mu\text{m}$ .

Two experiments with a Lithuanian glauconite mineral sample were made as well, these are reported elsewhere [10].

## Conclusions

Mineral carbonation has great potential for long-term storage of  $\text{CO}_2$  in Finland, where currently no competing options are under development apart from some work on increased utilization of  $\text{CO}_2$  in chemical processes or products. Besides energy sector and mineral/metal processing industry, it was found that also pulp and paper industry is an important sector to be considered. A  $\text{CO}_2$  pipeline network would be needed for  $\text{CO}_2$  transport from source to storage site at an elevated pressure that preferably exceeds the carbonation process pressure.

Chemical reaction kinetics studies on  $\text{Mg}(\text{OH})_2$  calcination followed by  $\text{MgO}$  carbonation in humid  $\text{CO}_2$  at pressures up to 35 bar is not necessarily speeded up under increased pressure levels. Reflecting this result the scarce literature on the issue suggests that carbonation of magnesium hydroxide,  $\text{Mg}(\text{OH})_2$ , seems preferable over magnesium oxide,  $\text{MgO}$ .

Fluidized bed carbonation studies suggest that magnesium carbonate,  $\text{MgCO}_3$ , product is removed from particles by attrition, abrasion, etc. and entrained from the reactor as fine particulates. A fluidized bed reactor appears to be a suitable reactor type, preferably operating at pressure levels similar to  $\text{CO}_2$  transport pressure, allowing the unavoidable pressure drop across the bed to be overcome. Pressurized fluidized bed reactor tests are needed as next step.

Still, as has been reported since the mid-1990s: chemical kinetics must be improved before technology can be further developed and scaled up. Eventually,  $\text{CO}_2$  sequestration at around 30 US\$ per ton  $\text{CO}_2$  should be achievable [5]. Realistic economic evaluations cannot be made until the mineral needed, which is now often considered a waste or useless by-product from a mining activity, receives a proper price tag.

## Acknowledgements

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