A Analysis of Carbon Dioxide Disposal in Carbonate Minerals

IB Chemistry HL

Research Question:

How feasible is the disposal of CO_2 by chemically combining it with calcium and magnesium oxides to create stable carbonates?

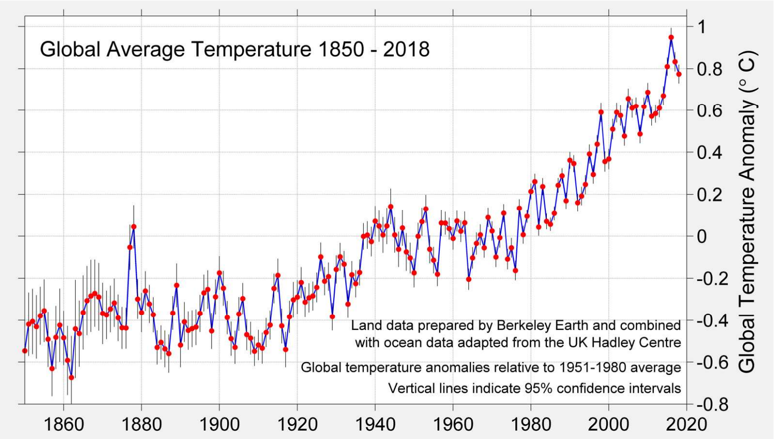
Introduction:

Personal Engagement:

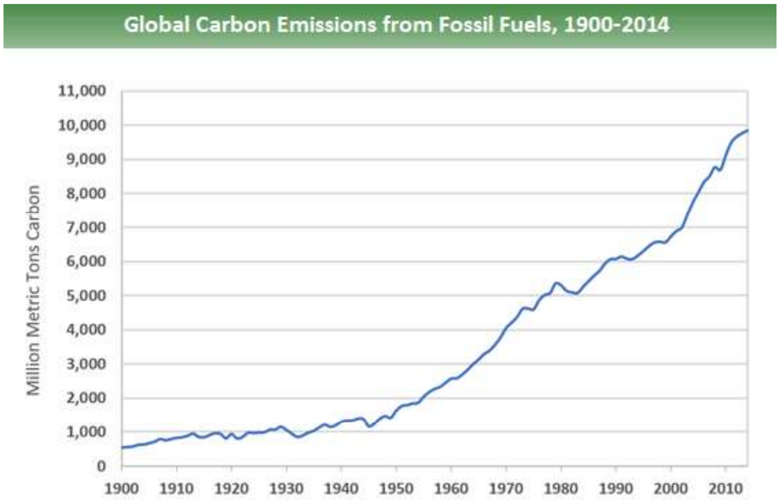
The idea for this investigation came from interest in environmental activism and the fight against the climate crisis. I am a passionate activist, and I believe that learning more about the science of climate change is necessary to be able to speak on it. I saw this as a great opportunity to learn more about this issue, so that hopefully I will be more effective in my activism and my ability to educate others in the future. After further reading about potential solutions to CO_2 emissions, I was interested in learning about the feasibility of these technologies and what it would take to justify their implementation. I was talking about these technologies with my father, who told me that he had worked on several patents about carbon dioxide disposal in carbonates with Columbia University scientist Klaus Lackner. This seemed like a great opportunity to learn about the topic I was interested in, while also having a starting point that was relevant to me.

Relevance:

This topic is relevant and significant in today's society due to the gravity of the climate crisis. CO_2 is a greenhouse gas, which are gases that accumulate in the atmosphere and trap heat, contributing to global warming. As the global CO_2 emissions increase, we can also see a distinct increase in global temperature. This is something that affects everyone.



"Global Temperature Report for 2018." *Berkeley Earth*, Berkeley Earth, 24 Jan. 2019, berkeleyearth.org/2018-temperatures/.



Boden, T.A., Marland, G., and Andres, R.J. (2017). Global, Regional, and National Fossil-Fuel CO2 Emissions. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tenn., U.S.A. doi 10.3334/CDIAC/00001_V2017.

Environmental and Ethical Concerns:

Due to growing attention for the climate crisis, a challenge currently being addressed by environmental scientists and chemists is the development of new methods to reduce carbon emissions and remove carbon monoxide pollution from our atmosphere. The technology that I am researching is a potential way to reduce carbon emissions that already exists, and could help to repair the damage to the environment.

Background:

Carbon dioxide levels in earth's atmosphere have increased by over 40% since the beginning of the Industrial Age. The concentration of CO_2 in the atmosphere has increased from about 280 parts per million to around 412 ppm since the mid-1700s.[8] In order to keep levels of atmospheric CO_2 stable, CO_2 emissions must be reduced by over 50% before 2050. The amount of CO_2 in the atmosphere poses an even higher risk than levels of other gases because it remains in the atmosphere for a long time, anywhere from 300 to 1,000 years.[1]

Investigation

A. Reactions being studied

In their most basic forms, the reactions that are being studied in this paper are as follows:

$$CaO + CO_2 \longrightarrow CaCO_3 + 179\ \text{kJ/mole}$$

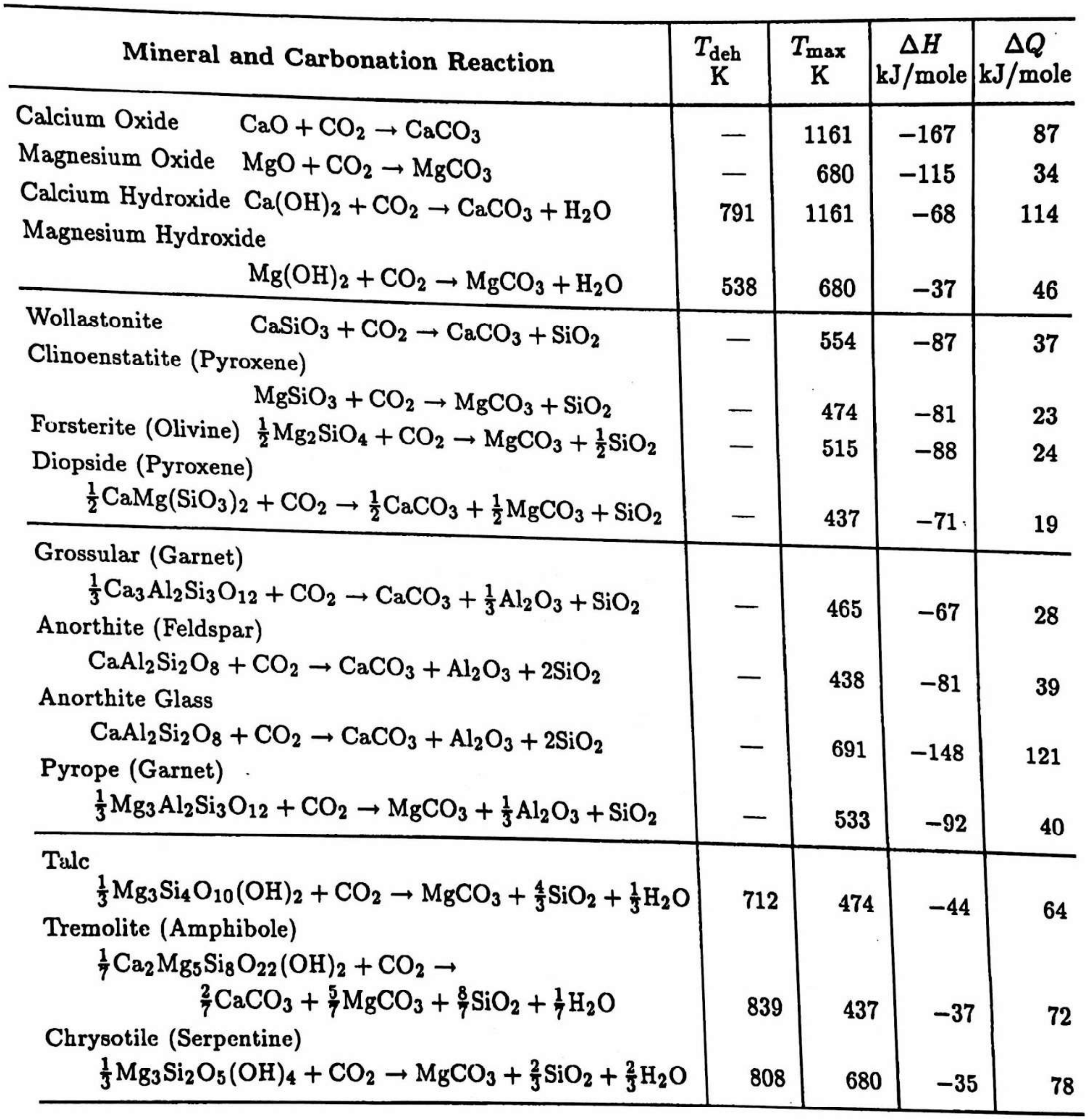
$$MgO + CO_2 \longrightarrow MgCO_3 + 118\ \text{kJ/mole}$$

B. Methodology

This type of reaction is a basic carbonation reaction, which occurs naturally, but very slowly, at room temperature. The purpose of Lackner's work was to find an efficient method of carbon dioxide disposal, so his experiments focused on accelerating this naturally-occurring reaction. He describes two different methods for the carbonation of calcium and magnesium oxides. The first method is a direct carbonation, which essentially takes gaseous CO_2 from the air and binds it with solid minerals. The second method is an aqueous process in which calcium and magnesium ions are extracted from minerals to form a solution, which is then precipitated to form the carbonate. Each of these approaches has its own advantages and disadvantages.

a. Direct Carbonation

Direct carbonation The following table shows the thermodynamic properties of direct carbonation reactions for a variety of different minerals.



Mineral and Carbonation Reaction		T_{deh} K	T_{max} K	ΔH kJ/mole	ΔQ kJ/mole
Calcium Oxide	$CaO + CO_2 \rightarrow CaCO_3$	—	1161	−167	87
Magnesium Oxide	$MgO + CO_2 \rightarrow MgCO_3$	—	680	−115	34
Calcium Hydroxide	$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$	791	1161	−68	114
Magnesium Hydroxide	$Mg(OH)_2 + CO_2 \rightarrow MgCO_3 + H_2O$	538	680	−37	46
Wollastonite	$CaSiO_3 + CO_2 \rightarrow CaCO_3 + SiO_2$	—	554	−87	37
Clinoenstatite (Pyroxene)	$MgSiO_3 + CO_2 \rightarrow MgCO_3 + SiO_2$	—	474	−81	23
Forsterite (Olivine)	$\frac{1}{2}Mg_2SiO_4 + CO_2 \rightarrow MgCO_3 + \frac{1}{2}SiO_2$	—	515	−88	24
Diopside (Pyroxene)	$\frac{1}{2}CaMg(SiO_3)_2 + CO_2 \rightarrow \frac{1}{2}CaCO_3 + \frac{1}{2}MgCO_3 + SiO_2$	—	437	−71	19
Grossular (Garnet)	$\frac{1}{3}Ca_3Al_2Si_3O_{12} + CO_2 \rightarrow CaCO_3 + \frac{1}{3}Al_2O_3 + SiO_2$	—	465	−67	28
Anorthite (Feldspar)	$CaAl_2Si_2O_8 + CO_2 \rightarrow CaCO_3 + Al_2O_3 + 2SiO_2$	—	438	−81	39
Anorthite Glass	$CaAl_2Si_2O_8 + CO_2 \rightarrow CaCO_3 + Al_2O_3 + 2SiO_2$	—	691	−148	121
Pyrope (Garnet)	$\frac{1}{3}Mg_3Al_2Si_3O_{12} + CO_2 \rightarrow MgCO_3 + \frac{1}{3}Al_2O_3 + SiO_2$	—	533	−92	40
Talc	$\frac{1}{3}Mg_3Si_4O_{10}(OH)_2 + CO_2 \rightarrow MgCO_3 + \frac{4}{3}SiO_2 + \frac{1}{3}H_2O$	712	474	−44	64
Tremolite (Amphibole)	$\frac{1}{7}Ca_2Mg_5Si_8O_{22}(OH)_2 + CO_2 \rightarrow \frac{2}{7}CaCO_3 + \frac{5}{7}MgCO_3 + \frac{8}{7}SiO_2 + \frac{1}{7}H_2O$	839	437	−37	72
Chrysotile (Serpentine)	$\frac{1}{3}Mg_3Si_2O_5(OH)_4 + CO_2 \rightarrow MgCO_3 + \frac{2}{3}SiO_2 + \frac{2}{3}H_2O$	808	680	−35	78

Lackner, Klaus S., et al. “Carbon Dioxide Disposal in Carbonate Minerals.” *Energy*, vol. 20, no. 11, 1995, pp. 1153–1170., doi:10.1016/0360-5442(95)00071-n.

T_{max} is the maximum temperature for carbonation at the pressure P_{CO2} = 1 bar.

T_{deh} is the dehydroxylation temperature at the equilibrium point where P_{H2O} = 1 bar.

ΔH is the enthalpy of the reaction.

ΔQ is the energy required to heat the mineral in the left column and CO_2 to whichever value is higher of T_{max} and T_{deh}.

In order for carbonation of many of these minerals to occur, they have to be heated to a very high temperature. However, the carbonation process of many of these minerals could theoretically be self-sufficient, since the energy that the carbonation process produces can in turn be used to heat more reactants, thus continuing the process. One possible environment for direct carbonation is in a "rotary kiln type operation or a fluidized bed process."[5]

b. Aqueous Process for Carbonation

This process requires the extraction of magnesium and calcium into an aqueous solution. There are several common methods of extraction, including using hydrochloric acid, sulfuric acid, or steam. After this, CO_2 can be added to form calcite or magnesite from the solution. Alternatively, calcium and magnesium hydroxides can be precipitated from the solution and then dry carbonation can occur separately.

Conclusion

According to the data collected by Klaus Lackner, there are at least two methods of carbon dioxide disposal via carbonation which are feasible to implement as possible solutions to the current problem with CO_2 emissions. The first method, direct carbonation, seems to be the more feasible solution, since it is less complex and requires fewer resources to implement. Carbon dioxide disposal via carbonation is a costly process, yet it is likely to become necessary in the coming centuries should the burning of fossil fuels continue at such a high rate. Additionally, the reaction provides its own heat energy, which reduces the cost of the process. While carrying this out in a structured environment is much more costly, there is an alternative method proposed by Lackner in his paper “Carbon Dioxide Disposal in Carbonate Minerals”. Lackner suggests pumping CO_2 into underground deposits of porous rock containing magnesium and calcium. Comparatively, there has already been research into underground disposal of CO_2. However, selecting areas with deposits of these specific minerals would facilitate the carbonation process, which will produce a permanent stable carbonate product. This poses fewer risks than the containment of CO_2 underground indefinitely. This is also a much lower cost process than the other proposed methods. Even though the low temperature environment of these deposits will hinder the reaction, the high pressure in these areas will also aid the process. The reaction will proceed more slowly than in the case of the other proposed methods, but will result in a stable, permanent disposal of CO_2 at a substantially lower cost. Using this technology, scientists will be able to work on removing CO_2 from the atmosphere and repairing the environment.

Endnotes

1. "The Atmosphere: Getting a Handle on Carbon Dioxide – Climate Change: Vital Signs of the Planet." *NASA*, NASA, 3 Mar. 2020, climate.nasa.gov/news/2915/the-atmosphere-getting-a-handle-on-carbon-dioxide/.
2. "Global Greenhouse Gas Emissions Data." *EPA*, Environmental Protection Agency, 13 Sept. 2019, www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data.
3. "Global Temperature Report for 2018." *Berkeley Earth*, Berkeley Earth, 24 Jan. 2019, berkeleyearth.org/2018-temperatures/.
4. Lackner, K. S., et al. "The Urgency of the Development of CO2 Capture from Ambient Air." *Proceedings of the National Academy of Sciences*, vol. 109, no. 33, 14 Aug. 2012, pp. 13156–13162., doi:10.1073/pnas.1108765109.
5. Lackner, Klaus S., et al. "Carbon Dioxide Disposal in Carbonate Minerals." *Energy*, vol. 20, no. 11, 1995, pp. 1153–1170., doi:10.1016/0360-5442(95)00071-n.
6. Lackner, Klaus. *Method for Producing a Moisture Swing Sorbent for Carbon Dioxide Capture from Air*. 15 Mar. 2016.
7. Lackner, Klaus. *Systems and Methods for Extraction of Carbon Dioxide from Air*. 20 Apr. 2010.
8. Nunez, Christina. "Carbon Dioxide Levels Are at a Record High. Here's What You Need to Know." *Carbon Dioxide in the Atmosphere Is at a Record High. Here's What You Need to Know.*, National Geographic, 14 May 2019, www.nationalgeographic.com/environment/global-warming/greenhouse-gases/.