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DEVELOPMENT OF A SEMI-CONTINUOUS EX-SITU CARBON DIOXIDE MINERALIZATION PROCESS UTILIZING FLUE GAS AND PRODUCED WATER STREAMS

A Thesis

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by

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Literature Review

The effects of increasing concentrations of CO_2 on global systems can already be felt and will only continue to increase in magnitude as emissions continue. Figure 1, reproduced from a study by Soloman, et al., demonstrates the potential global warming effects of increased CO_2 concentration in the coming millennium.[1]

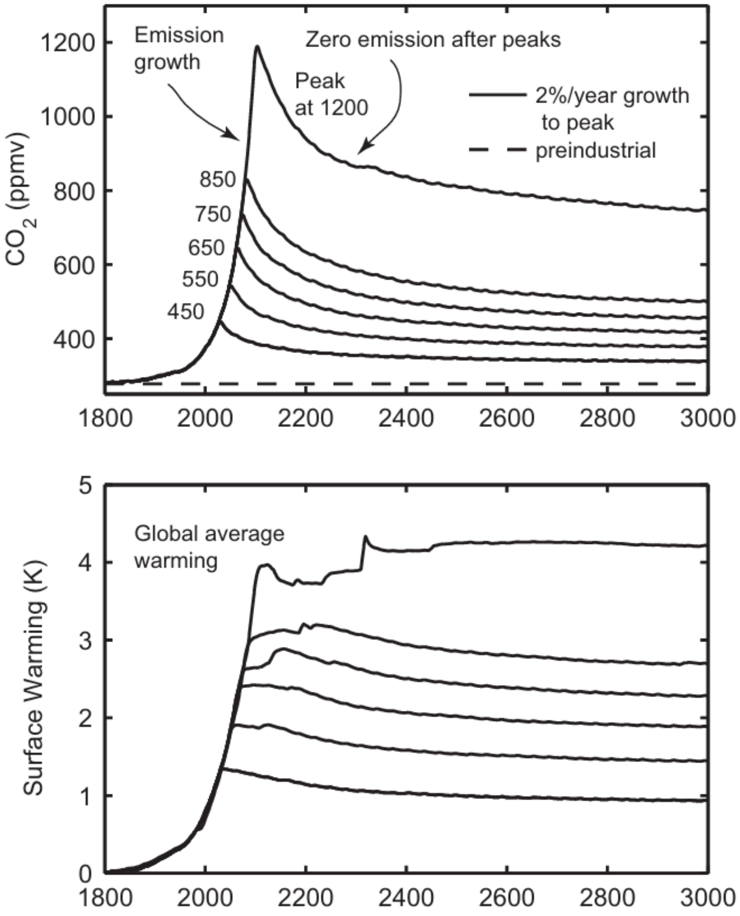

Figure 1. *Top graph represents the potential increases in global CO_2 concentration (ppmv), while the bottom graph represents the potential global surface warming associated with those concentration increases. Reproduced from Soloman, et al.*[1]

The Intergovernmental Panel on Climate Change (IPCC), in their 6th report on international climate, gathered information from journal articles and governmental entities around the world to summarize the effects of climate change on natural and human systems. In this report, the IPCC recommended that global warming must be limited to below 2°C higher than pre-industrial temperature to prevent significant impact on global populations and ecosystems. This report also includes a literature review and assessment of the ways in which climate change could be mitigated through human effort. One of the conclusions that the IPCC reached was that the post combustion capture of CO_2 will prove critical to averting a climate crisis.[2] Further reviews of emerging mitigation methods corroborate the idea that in order to prevent warming above 2 °C, the capture of CO_2 is strongly recommended.[3] One promising route for removal of CO_2 is the implementation of carbon capture and storage (CCS) technologies. CCS technologies involve capturing and storing CO_2 in a manner that the CO_2 will not reenter the atmosphere on reasonable timescales. A review of various CCS methods and their implementation is available in a paper by Bui, et al.[4] If captured carbon is utilized to create useful chemicals, in a process known as carbon capture, utilization, and storage (CCUS), costs associated with the capture of carbon can be offset. However, many current CCUS technologies (as described by Singla, et al.) are costly and inefficient, with improvements needed to become viable CO_2 capture solutions.[5] The creation of more cost effective and efficient methods of capturing CO_2 is needed to achieve wide adoption of CCUS technologies.

One promising method of CCUS is carbon mineralization, which is described in a report by Huijgen as a process wherein "…gaseous carbon dioxide is converted into a solid carbonate in an industrial imitation of natural weathering processes involving alkaline silicate minerals."[6] Early efforts in CO_2 mineralization were described in a 1995 study by Lackne, et al., which introduces the basics of mineralization and describes two methods of CO_2 disposal in carbonate materials, one that relies on solid-gas interactions at very high temperatures, and one that utilizes reactions in an aqueous solution.[7] A typical mineralization reaction involves the conversion of CO_2 into carbonate minerals by combination with an alkaline cation, as in the general reaction presented by Cao, et al.[8], shown below as Eq. 1.

$$\mathrm{Ca^{2+}, Mg^{2+}, Fe^{2+} + CO_2 + H_2O \rightleftharpoons (Ca, Mg, Fe)CO_3 + 2H^+} \qquad \text{Eq. 1}$$

Mineralization occurs primarily in two different environments: *in situ* and *ex situ. In situ* mineralization is a CCS process that occurs when CO_2 is injected into geological formations that contain alkaline substances, such as underground basins or volcanic shale, where it can be stored long term. The process and common examples are described in a review by Romanov, et al.[9] Mineralization can also occur *ex situ*, via an engineered process that utilizes alkaline waste streams to produce carbonates above ground in processing facilities. Gerdemann, et al. describes a common example of the *ex situ* mineralization process that involves the use of ultramafic (high Mg content) rocks to capture carbonates in the form of $MgCO_3$.[10]

While *in situ* mineralization is a viable option for long term storage in some areas, the process is slower than *ex situ* mineralization due to the slow process of cation dissolution from geological formations (hindered by sluggish dissolution reaction kinetics), and is dependent on regional hydro- and geological conditions as described in a study by Snæbjörnsdóttir, et al.[11] Further, the *ex-situ* process can be tailored to produce value added solid carbonate products, as described in a report from the National Energy Technology Laboratory by O'Connor, et al.[12] Studies by Hepburn, et al. and Hills, et al. describe how the products of CO_2 mineralization can help the process fit into the economic landscape of CCUS technologies[13,14] by entering the growing market for carbonate materials, like the market for precipitated $CaCO_3$, which is currently valued at $1.9 billion according to a report by Grand View Research.[15]

Ex situ mineralization relies on the availability of low-cost alkaline feedstock to mineralization CO_2 into carbonates. Bullock, et al., Assima, et al., and Oskierski, et al. all describe a mineralization process similar to the study by Gerdemann, et al. that uses solid waste from mining, called mine tailings, as a source of alkaline feedstock.[16–18] This process involves the grinding of mined ore to a suitable size, heat treatment to remove water, creation of a slurry, and the usage of high-pressure CO_2 to form carbonates. To quantify the ability of different materials to capture carbon, the study by Gerdemann describes the potential maximum amount of CO_2 that could be captured in a particular material as the carbonation potential, often measured in gCO_2/kg or gCO_2/L and denoted as carbonation potential. Carbonation potential depends on the chemical composition of the minerals described, specifically the amount of alkaline material available to form carbonates.

Various mineralization studies utilizing solid alkaline materials involve different approaches for mineralization processes. Bullock, et al. describes the potential for metal and diamond mine tailings to capture carbon on an accelerated timescale, compared to the natural process of weathering (the uptake of CO_2 by minerals), which they estimate would achieve a maximum of 21% of their carbonation potential within timescales <50 years.[16] Assima, et al. studies the usage of magnesium rich mine wastes from nickel mines to capture concentrated CO_2 on a more rapid timescale than natural uptake in lower concentrations of CO_2 found in the atmosphere.[17] Oskierski described the natural process by which mine tailings from the Woodsreef Asbestos Mine uptake carbon, and provides extensive mineral information, as well as input on how this natural process could be accelerated for more rapid carbonation.[18] Hamilton, et al. describes some of the risks associated with transition metals found in the material used for CO_2 capture, and how they could potential be recovered.[19]

Mine tailings have a high potential for carbonation, and their usage may provide a valuable route for the capture of CO_2. However, in all cases, the processing of solid alkaline materials for redissolution is a costly and energy intensive process that lowers the efficiency of processes, as described in a study by Renforth, et al.[20] The dissolution of the ground tailings tends to limit the reaction with CO_2, resulting in a less efficient process. Reviews of the recent developments in the field of mine tailings-based mineralization suggest that further improvements to the kinetics and mass transfer of CO_2 are needed. Zhang, et al. describe the high energy consumption of several steps in the mine tailings mineralization process, including feedstock grinding and slurry stirring.[21] A review by Pan, et al. describes the need for a better designed reactor to enhance the mass transfer of CO_2 between the gas, liquid, and solid phase to facilitate the carbonation reaction.[22]

A more economical process of CO_2 mineralization can be developed by utilizing liquid waste streams with already dissolved Ca^{2+} and Mg^{2+} ions, such as produced water (PW) brines, the biproduct of oil and natural gas production. Liu, et al. conducted a study on the usage of PW for CO_2 mineralization utilizing carbonic anhydrase to accelerate the process of CO_2 mass transfer from gas to liquid further, demonstrating that mineralization utilizing brines with high aqueous alkaline content was very feasible.[23] The use of liquid alkaline material not only increases the mineralization efficiency, it also saves costs and energy requirements associated with the grinding and dissolution of solid materials for use in carbon capture. An example of a mineralization reaction in water is the formation of calcium carbonate. The Ca^{2+} ions present in water can be used to form precipitated calcium carbonate (PCC) via the reaction shown in Eq. 2

$$\mathrm{Ca^{2+}(aq) + CO_3^{2-}}(aq) \leftrightarrow \mathrm{CaCO_3}(s) \qquad \text{Eq. 2}$$

The PCC formed by this reaction is a fine white powder with high market value if produced with a high purity. PCC has markets value as a filler for paper, plastics, paint, food, and pharmaceutical products as described by various industrial handbooks.[24,25] PCC forms in 3 primary polymorphs: aragonite (needle-like rods), vaterite (disk shaped plates), and calcite (cubic structures), described in a report by Jimoh, et al.[26] While each polymorph has industrial value, a report by Chang, et al. describes the thermodynamic stability of the three polymorphs, and concludes that calcite has the highest stability, leading to it having a higher value as an industrial product.[27] Therefore, to increase the economic viability of PCC-producing processes, the formation of calcite should be targeted.

The formation of carbonates is dependent on the formation of the carbonate ion (CO_3^{2-}), formed via the reactions shown in Eq. 3 and 4.

$$\mathrm{CO}_{2(aq)} + \mathrm{OH^-}(aq) \leftrightarrow \mathrm{HCO_3^-}(aq) \qquad \text{Eq. 3}$$

$$\mathrm{HCO_3^-}(aq) + \mathrm{OH^-}(aq) \leftrightarrow \mathrm{H_2O}(l) + \mathrm{CO_3^{2-}}(aq) \qquad \text{Eq. 4}$$

Eq. 3 and 4 occur simultaneously in water when CO_2 is bubbled. A study by Millero on the carbon dioxide systems present in the ocean studied this phenomenon and observed that the thermodynamic favorability of each reaction is determined by pH. Additionally, the study observed that Eq. 4, the equation that forms the CO_3^{2-} ion necessary for the formation of $CaCO_3$ is driven to the right at elevated (>8) pH, leading to the formation of CO_3^{2-} ions.[28] To this end, studies of CO_2 mineralization utilizing PW brines typically involve the one-time addition of NaOH to titrate brines to a suitable elevated pH for mineralization.

Experiments performed by Zhu, et al., which provided the basis for the experimental setup used in this study, employed this method to raise the pH of the PW brines to 10.5 before beginning to bubble CO_2 into the brine, leading to the formation of CO_3^{2+} and the mineralization of $CaCO_3$.[29] A similar method was of titration was used in mineralization experiments conducted by Wilson, et al. and Harrison, et al., both of which sought to form carbonate ions for mineralization.[30,31] The titration method effectively mineralizes CO_2 into $CaCO_3$ from PW brines via CO_2 bubbling. However, upon the addition of CO_2, a gradual drop in pH due to the consumption of OH^- prevents the complete mineralization of Ca^{2+} to calcite, due to lack of CO_3^{2-} formation. This leaves the process well below its maximum carbonization potential. In the case of the experiments performed by Zhu, et al., the brines reached only a fraction (at most 16%) of their potential assessed based on Ca^{2+} and Mg^{2+} content.[29]

Because the formation of carbonates is associated with elevated pH, if the pH were maintained within the desired range for mineralization, it is hypothesized that a semi-continuous mineralization reaction could be achieved and greatly enhance the achieved carbonation potential. To maintain the reaction pH, the continuous addition of a base (such as NaOH) would counteract the pH drop due to OH^- consumption.

The industrial implementation of the proposed semi-continuous mineralization technology aimed at producing calcite would require a caustic or NaOH solution to shift the dissolved CO_2 through Eq. 3 and 4, a CO_2 source, and a concentrated stream of aqueous Ca^{2+}. A suitable quantity of NaOH for industrial implementation may be provided by the chlor-alkali process, which produces gaseous chlorine and NaOH for commodity uses, as described in a report by Gong, et al.[32] An ideal choice for a source of CO_2 is flue gas, the gaseous waste product of a number of industrial processes, including energy generation via fossil fuel combustion, steel manufacturing, and others. A study by Ho, et al. describes the benefits of utilizing flue gas as a CO_2 feedstock due to its high CO_2 content (6-30% CO_2 by volume), which enables the foregoing of CO_2 pressurization and purification processes that are energy, cost, and land intensive.[33] Samanta, et al. describe a study involving the usage of flue gas as a CO_2 source for a capture process using solvent sorbents, proving an example of the viability of flue gas as a feedstock for CO_2.[34] Lastly, the utilization of PW can supply the requisite aqueous Ca^{2+} and doubly serve as a waste mitigation process by reducing the hardness ion content of the brines, thereby increasing opportunities for reuse. The benefits of reducing hardness via treatment for reuse is described in a study on disposal of brine in marine environments by Ahmad and Baddour.[35] Thus, the combination of flue gas CO_2 sequestration, integration with the chlor-alkali process, and PW as a reaction medium supplying Ca^{2+} is proposed as a route toward economical CO_2 mineralization to $CaCO_3$ products.

Research Question and Approach

This study explores the development of a semi-continuous mineralization reactor and the thermodynamic considerations of operating the mineralization reaction at various pH and temperatures. A full factorial design of experiments was conducted to study the effects of reaction conditions on the rate of $CaCO_3$ mineralization and carbon capture utilizing synthetic PW brines and synthetic flue gas. The flue gas composition, temperature of reaction, and pH were varied because they are likely to affect the mineralization rate based on Henry's law (flue gas composition and temperature) and carbonate speciation (pH). The effects of reaction conditions on the morphology of solid precipitants were also studied to ensure that high value (calcite) products were formed.

Contextualization of Research Methods

The core mechanisms of this research are based on two desired outcomes: the decarbonization of human processes, and the softening of produced water. First and foremost, human activities towards decarbonization are the main goal. The reduction and eventual removal of CO_2 emissions is critical towards maintaining Earth – Steffan, et al. describe the potential effects on earth systems if these changes are not made, including potential tipping points towards a "Hothouse Earth."[36] The process by which systems (primarily human) are changed to prevent further carbon emissions is called decarbonization. Rockström, et al. describe the kinds of changes that could be made in decarbonization efforts, splitting them into four categories: innovation, institutions, infrastructures, and investment.[37] Additionally, these changes target three main sectors: reduction of global CO_2 emissions, CO_2 removal, and CO_2 reduction of land use based CO_2 emissions. Figure 2 outlines the timeline of changes with the highest probability to prevent 2°C of warming from occurring.

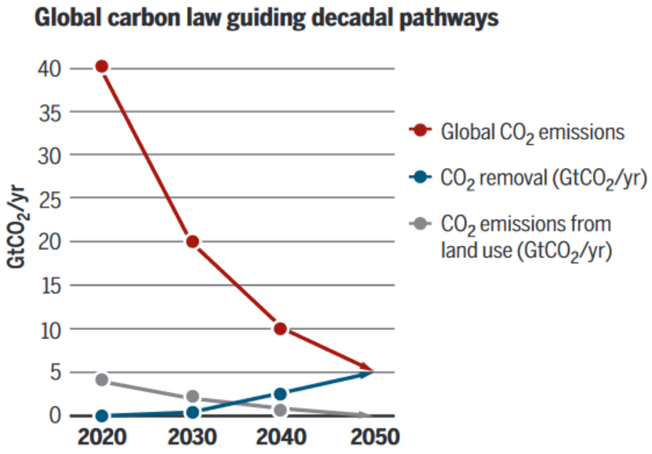

Figure 2. *Graph showing potential changes in global carbon law over the next 30 years. Reproduced from Rockström, et al.*[37]

While CO_2 removal has a role to play in the prevention of 2°C of warming, the reduction of global CO_2 emissions should be considered a top priority, hence the project's focus on using novel methods to reduce emissions from flue gasses. Different regions of the world have different methods of CO_2 reduction that they are best suited for – Iceland, for example, is well suited for geological storage, due to an abundance of porous volcanic rock such as basalt that readily reacts with CO_2.[38] In a similar vein, Ohio University is located atop the Marcellus Shale, a geologic basin that contains vast quantities of calcium, well suited for mineralization reactions.[39] Figure 3 shows the coverage of the Marcellus shale.

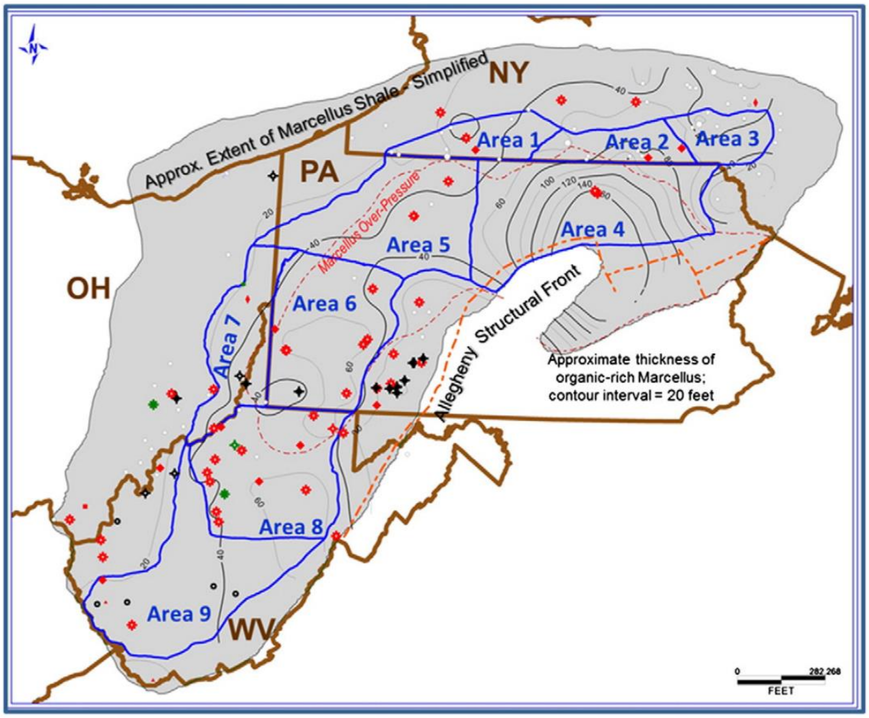

Figure 3. *Map showing approximate coverage of the Marcellus Shale. Reproduced from Godec.*[39]

The composition of the Marcellus basin can be found from studies done by Chapman, et al,[40] Shih, et al,[41] and Blondes, et al.[42], shown below in Table 1.

Component	**Ion**	**(mg/L)**	**(mol/L)**
Chloride	Cl^-	66000	1.86
Calcium	Ca^{2+}	9000	0.22
Magnesium	Mg^{2+}	900	0.04
Potassium	K^+	400	0.01
Sodium	Na^+	28000	1.22
Barium	Ba^{2+}	2000	0.01
Strontium	Sr^{2+}	2000	0.02

Table 1: Composition of Marcellus Brine

This composition formed the basis for the synthetic brines created in this study. Of note is the high calcium concentration – if all the calcium were to be mineralized as $CaCO_3$, a carbonation potential of 9.9 g $CO_2 \cdot L^{-1}$ brine could be achieved. Additionally, while Mg^{2+} ions have the potential to form $MgCO_3$, in the final industrial scale process, the Mg^{2+} ions will be removed prior to the bubbling of CO_2 via precipitation as $Mg(OH)_2$ (Brucite) to avoid competing consumption of hydroxide ions. Mg^{2+} ions were included in preliminary experiments to study the effects of a one-time vs continuous addition of NaOH, but were excluded from the main block of experiments. Also of note are Ba^{2+} and Sr^{2+}, both of which have the potential to form carbonates. Simulations performed prior to starting experimentation indicate that the formation of $CaCO_3$ is heavily favored, so to simplify experiments, Ba^{2+} and Sr^{2+} were also excluded from synthetic brines. Continued experiments have been conducted on the effect of these cations on mineralization rate and precipitate, but these studies were not discussed as a part of this report. The final synthetic composition includes only the chloride, calcium, potassium, and sodium ions.

The usage of produced water has additional benefits beyond the capture of CO_2 – the decreased Ca^{2+} and Mg^{2+} concentrations in the PW discharged from our reaction setup lowers the hardness of the water. The discharge of high salinity PW causes several environmental issues, and thus typically requires an energy and environmentally intensive processes as described in studies by Ghernaout and Jiménez, et al. on the desalination of PW brines. and a great deal of work has been put into addressing this issue.[43,44] Typically PW is simply reinjected into the well from which it originates, a phenomenon that Eyitayo, et al. describes occurring in 90% of cases.[45] However, several different methods exist for treating PW. The precipitation of Ca^{2+} and Mg^{2+} ions as calcium carbonate and brucite respectively offers an innovative way to deal with this issue. Additionally, through the usage of produced water, the water usage of the mineralization process is reduced by not requiring clean freshwater to be used for dissolving ground mined minerals, a benefit that Eyitayo, et al explores in some depth.

Continuous Reactor Setup

As previously mentioned, work by Zhu, et al. formed the basis for the setup used in these experiments. Their work provided a foundation for bench scale mineralization experiments utilizing produced water and CO_2 bubbling. The usage of a jacketed reactor for temperature control, a sparger to increase bubble size, and sampling methodology all were based on the work by Zhu, et al.[29] However, a batch style reaction such as the one present in Zhu, et al. is not suitable for industrial implementation of this technology. The limitations of the batch reaction, such as achieving only a fraction (16%) of carbonation potential, had to be addressed before scaling up. Our decision to perform semi-continuous mineralization reactions via continuous addition of NaOH was based heavily on the observations of Zhu, et al. that calcite production halted below a certain pH (~6), because of not having the OH^- ions necessary to form carbonates. This process, which allows brines to reach 100% of their carbonation potential, is considered semi-continuous due to the batch nature of only using 1 L of brine at a time. Studies are continuing at OU using a similar methodology, but with a larger reactor. Currently, the maximum size tested has been a 30 L reactor, where a 100% carbonation potential was achieved within 6 hours of operation. While the batch nature of the brine is still the limiting factor in making a continuous reaction, this reactor setup has succeeded in mineralizing 6 kg of carbon per day, a large step towards the project's end up goal of mineralizing 10 kg per day.

Reaction Conditions

The decision to study flue gas composition and reaction temperature's effects on the mineralization rate was based largely on Henry's law, a fundamental law of thermodynamics that describes the solubility of gases in water. Henry's law is shown in Eq 5.

$$\mathrm{C}_g = k\mathrm{P}_g \qquad \text{Eq. 5}$$

In this equation, C_g represents the concentration (or solubility) of a dissolved gas in a liquid, k represents the Henry's law constant, and $P_g$represents the partial pressure of a gas about a liquid. Prior studies on the effects of increased partial pressure of CO_2 on mineralization rates studies found that increased partial pressure increases CO_2 solubility, which leads to increased production of carbonate ions and increased mineralization rates.[31,46] These studies utilized artificial methods of increasing CO_2 pressure through compression of atmospheric gasses, which requires energy and can decrease efficiency. Our study chose to utilize flue gasses, which already have high concentrations of CO_2, to increase the energy and cost efficiency of this process. Specific concentrations for testing were chosen were chosen based on studies of flue gas compositions from coal (Granite, et al.)[47] and natural gas (Weber, et al.)[48] fueled power plants for a low value of 10% CO_2, with a high value of 25% CO_2 chosen to represent processes such as industrial steel production (Kuramochi, et al.).[49]

Another method to increase the solubility of CO_2 is to increase the value of the Henry's law constant. As shown in studies by Crovetto, et al. and Sanders, et al., in a CO_2-H_2O system, temperature has a significant effect on Henry's law constant and thus gas solubility.[50,51] These studies showed that as temperature increases, CO_2 solubility decreases, which resulted in a decreased mineralization rate, a result that was consistent with our observations. The exact temperatures were chosen to represent a room-temperature reaction (25°C) and a reaction where temperature is consistent with the typical output temperature of NaOH from the chlor-alkali process, as described in a report by Li, et al.[52]

For a third reaction condition, pH was chosen for two reasons. The pH of a reaction, as described earlier in this report, affects the speciation of carbonates formed within the brine, leading to potential effects on mineralization rate. The effects of pH on carbonates can be observed in a number of studies, including one by Rinder, et al.[53] However, the pH of the reaction also affects the formation of carbonates. As explored in a number of studies conducted by Chang, et al.[54], Sun, et al.[55], Zhu, et al.[56], and Wang and Becker[57], the different forms of calcium carbonate exhibit significantly different morphologies, leading to different stabilities. Generally, the morphology (as discussed in work by Sun, et al.) progress in order of increasing stability from amorphous calcium carbonate to vaterite to aragonite to calcite. However, the pH of the solution can also affect morphology, leading to different final morphologies that do not transform into calcite. Tai, et al.[58], Han, et al.[59], and Spanos et, al.[60] discuss the effects of pH on morphology, and how by affecting CO_3^{2-} saturation Studies such as these informed the decision to study reaction pH as a parameter for mineralization. Synthetic brines created for experimentations typically had a pH close to 8, so this value was chosen to represent a low pH environment, while pH 9 was chosen to represent a higher pH. Further studies are being conducted involving higher pH environments.

Source of Funding

The research on this project was conducted as part of a larger project on CO_2 mineralization being conducted at Ohio University's Institute for Sustainable Energy and Environment (ISEE). The project was led by Dr. Jason Trembley, Professor of Mechanical Engineering. Funding was provided by the Department of Energy and National Energy Technology Lab, DOE Number DE-FE0032258.

Timeline of Work

The project began in July 2023, with preliminary experiments focused on developing the semi-continuous process taking place from July through December of 2023. Once the process had been developed, research on the effect of reaction conditions was conducted from January 10th, 2024 through March 8th,2024. Sample processing took place continuously during this period, concluding in March 2024. During April 2024, this work was presented publicly at two different events, the Multidisciplinary Honors Conference and the OHIO Student Expo. A draft of the manuscript was completed in March 2024 as well, but most of the work on the manuscript took place from May 2024 through September 2024, when the manuscript was deemed in a final draft to share with co-authors. Beginning in September 2024, final revisions to the manuscript were made, and on October 8th the manuscript was submitted for publication at Energy Science and Engineering. Also in October, results were publicly presented again at the American Institute for Chemical Engineers (AIChE) Annual Conference and Student Conference in San Diego. At this point, work on the other component of the thesis began while waiting for a decision. On January 17th, 2025, feedback was finally received from the journal. Comments were responded to, and on February 21st, the manuscript was resubmitted with changes made. On April 15th, 2025, the manuscript was accepted for publication, and a final copy was submitted.

Author Contributions

The contributions of each author on the manuscript are as follows:

Quinn Bennett:

As the head of this project and the lead author, I have completed most of the work present in the manuscript. I did work to complete the literature review prior to beginning this stage of the project, including investigating mineralization methods and contextualizing our study. I assisted with the selection of the reaction components tested, doing literature review on the nature of mineralization reaction and which factors might influence them. Once the test conditions had been selected, I planned out the experimental matrix that was used for most experiments on this project. Once experiments had been planned, I was present for most reactions conducted, where my duties included setup, operation, and tear down/cleaning of the 1 L reactor and its components. When I was not present for experiments, I was communicating with team members to ensure successful competition and help with troubleshooting.

Once sample collection was complete, I completed the majority of sample analysis, including operation and some maintenance of ICP-OES equipment, and the creation of standards for analysis. I also completed XRD analysis of samples, and took photos using the SEM. After samples had been analyzed, I processed and analyzed the data, including the creation of graphs and figures that would eventually be used in publication. Once the data had been analyzed, I began writing the publishable manuscript. This included completing a full literature review, writing methodology, results and discussions sections, and the creation of figures for publication. I worked with Dr. Kody Wolfe to refine the manuscript to a publishable state, and his input was invaluable in preparing the manuscript to its current state. Once the manuscript was in a suitable state, I solicited feedback from several people listed as co-authors and responded accordingly to their comments. When the manuscript was deemed ready by me and Dr. Wolfe, we submitted the manuscript for publication in Energy Science and Engineering. Once feedback was received, I responded to reviewer comments and made necessary changes to the manuscript, and the manuscript was resubmitted for publication.

Kody Wolfe:

Dr. Kody Wolfe is a research engineer at the ISEE, and as my thesis advisor, his contributions to this project were invaluable. Dr. Wolfe served as a mentor throughout the duration of the project and was present for all parts of this research. Dr. Wolfe did an initial literature review, including researching previous CO_2 mineralization in produced water studies, leading to the decision to base our experiments largely on those found in Zhu, et al. He served as a major contributor when developing the reactor setup and planning experiments, including ordering materials and assembling the reactor setup used for experiments.

Dr. Wolfe assisted with many of the experiments performed during this study and helped to train me on the usage of ICP-OES, XRD, and SEM equipment. Additionally, he assisted with the analysis of data and with troubleshooting on the equipment used to analyze samples. Once initial experiments had been completed, Dr. Wolfe served as an editor and large contributor to the manuscript writing process. We had weekly meetings to discuss progress, and he gave feedback on the manuscript as it progressed. Dr. Wolfe also taught me various figure making techniques so that the figures in the manuscript could be as high quality as possible. When the manuscript was completed, Dr. Wolfe led the submission process, and once comments from reviewers were received, he once again served as an editor and lead on the resubmission process.

Andrew Kasick:

A PhD student at the time of the project (recently having passed his defense) conducting research at the ISEE, Andrew contributed a great deal of time and energy to the completion of the research on this project. He assisted with the initial setup of experiments, and helped a great deal with the preparation, execution, and clean-up of experiments. Andrew took the lead on a smaller side project when an issue with the schedule of drying samples was affecting the morphology and conducted an experiment to determine the exact cause of this. Once the manuscript was nearing completion, Andrew provided feedback that improved the quality of the work.

Reggie Shaffer:

An undergraduate researcher working at the ISEE, Reggie helped with preparation, execution, and clean-up of experiments. While he did not contribute directly to the manuscript, his help on the project warranted a co-authorship.

Edward Nyameke:

A PhD candidate, Edward joined the project in January 2024. His contributions to the project included assistance with the operation of the mineralization reactor and completing a literature review containing several sources which were cited in the paper.

Omar Movil-Cabrera:

Dr. Movil-Cabrera joined the ISEE as a Research Engineer later in the project (March 2024) to help relieve some of the work on other aspects of the project from Dr. Wolfe. His contributions to the project include assisting with several experiments, and contributing feedback once the manuscript was in a completed state.

Matthew Thackery

Matthew Thackery, an undergraduate student at Ohio University, assisted with the setup of the reactor, including calibrating pumps, as well as conducting titrations to study precipitation plateaus of the PW brines.

Shubhashini Oza:

A member of Brown & Caldwell, an environmental engineering consulting firm, Dr. Oza contributed expertise on water chemistry towards the project. Late in the manuscript writing process, she provided the data necessary for the creation of Figure 3, concerning the phase diagram of carbonate ion formation and how pH/temperature can affect this.

Jason Trembly:

Dr. Jason Trembly, professor of mechanical engineering and PI at the ISEE, was responsible for securing the grant that funded this project. Dr. Trembly also provided feedback during the manuscript writing process, as well as during the process of writing the thesis component.

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