Frontier

Minerali

Carbon Dioxide Removal Purchase Application

Fall 2022

General Application - Prepurchase

(The General Application applies to everyone; all applicants should complete this)

Company or organization name

Minerali

Company or organization location (we welcome applicants from anywhere in the world)

Cambridge, MA

Name(s) of primary point(s) of contact for this application

Mirza Cifric, Admir Masic

Brief company or organization description

Minerali is developing low cost scalable systems for CO_2 mineralization and permanent storage.

1. Project Overview[1]

a. Describe how the proposed technology removes CO_2 from the atmosphere, including as many details as possible. Discuss location(s) and scale. Please include figures and system schematics. Tell us why your system is best-in-class, and how you're differentiated from any other organization working on a similar technology.

<u>Summary</u>

Minerali uses seawater or brine electrolysis to produce highly reactive brucite slurries that directly mineralize CO_2 in ambient air and other CO_2 sources. Distinct from physical (liquid) CO_2 storage, direct air capture (DAC) via mineralization chemically incorporates atmospheric CO_2 into carbonate minerals,

[1] We use "project" throughout this template, but note that term is not intended to denote a single facility. The "project" being proposed to Frontier could include multiple facilities/locations or potentially all the CDR activities of your company.

which are indefinitely stable over geologic time scales. Of these processes, the transformation of hydrated brucite ($Mg(OH)_2$) into magnesite ($MgCO_3$, the magnesium-containing analogue of limestone) under ambient temperature and pressure is an energy efficient and attractive avenue for CO_2 removal because it is permanent, highly thermodynamically favored,[1,2] and relatively rapid, with nearly complete conversion of brucite into magnesite occuring in under a year.[3,4,5] By leveraging modern materials characterization tools and expertise that are available through our academic and industrial collaborators, Minerali has the unique ability to scale the production of brucite for DAC from one of the most abundant sources on earth: the ocean.

Our Rationale

The reactive capacity of brucite as a carbon sink is effectively unlimited considering the high abundance of dissolved Mg^{2+} in seawater. While the concentration of magnesium in seawater is ca. 1300 mg/L, waste brines from desalination plants can contain up to ten times this amount.[6,7,8] Using our electrochemical approach for the precipitation of brucite, achieving our proposed 1,000 tonnes of carbon dioxide removal (CDR) would only require ca. 430,000 m^3 of brine (<0.5% of the global daily 140 million m^3 brine production).[8,9] As such, desalination waste streams provide an abundant and economically appealing Mg^{2+} source for high efficiency brucite production and solid-phase CDR.

While the natural tendency of brucite to fix carbon (when wet) is well documented *in-situ* (e.g. in mine tailings piles[10,11,12,13,14] and magnesia cements),[15,16] there is remarkably little research on the *ex-situ* mineralization of newly synthesized material. Our current work focuses on fabricating large amounts of crystallographically pure, CO_2-mineralizing brucite to ultimately leverage the material's proven DAC tendencies and high reactive surface area properties.[3,11,12,13,17] At the laboratory scale, our preliminary results reveal that brucite can be precipitated in remarkably large quantities under optimized seawater and brine electrolysis conditions.

Given these promising results, it is worth noting that most brine-based DAC studies focus on calcium-based precipitates.[16,17] Notably, however, brucite's thermodynamic tendency to become magnesite (ΔG = -1,026.0 kJ/mol vs. ΔG = - 590.8 for calcite-type carbonates)[1,2] means that the energy required to electrochemically synthesize reactive magnesium compounds is considerably lower than for calcium-based mineral phases.[3,17,18] Moreover, the concentration of Mg^{2+} in seawater is more than 3x the concentration of Ca^{2+} (ca. 400 mg/L), potentially leading to more scalable outcomes for electrolysis-based CDR.[8,16]

Therefore, the conversion of brine-derived brucite into indefinitely stable carbonates is a game changer in the search for fast, efficient, and low-cost carbon mineralization.

Our Approach

Minerali's ultimate goal is to create a bolt-on CDR solution for desalination facilities and other seawater sources that minimizes additional energy requirements associated with the transportation of precipitated products from their site of manufacture to their site of use. To that end, the optimization of brucite precipitation reaction conditions for a broad range of sea-surface temperatures and salinities is a key priority.

Through this approach, we aim to produce a high-quality source material for the permanent and economical sequestration of CO_2 from industrial sources and through direct air capture. The byproducts of this reaction can be used for building and road construction, agriculture, or can be safely buried for long-term storage. After synthesis, brucite can remove CO_2 directly from the atmosphere as the slurry dries, where the magnesium hydroxide is converted into environmentally stable magnesite ($MgCO_3$). In this process, each molecule of brucite converted to magnesite absorbs one molecule of CO_2 from the atmosphere: $Mg(OH)_2 + CO_2 \rightarrow MgCO_3 + H_2O$.

The brucite precipitation process is driven by the electrolysis of seawater in response to a very low voltage. To ensure a steady concentration of Mg^{2+} for the precipitation of brucite, we continuously pump new brine through the system at a throughput of up to 15 volumes per hour at our experimental seawater facility. The ability to independently control the flow rate and temperature is critical to providing the wide range of experimental conditions we need to advance our commercially-oriented research.

While the exact kinetics and efficiencies of these reactions have yet to be fully elucidated, the scientific consensus is that full conversion of wet brucite to magnesite occurs in open air conditions over the course of about one year.[3,4,5] The rate of formation of $MgCO_3$ via brucite is on the order of 3×10^{-8} moles m^{-2} s^{-1}, whereby mineral conversion kinetics are rate limiting.[4,5,19] Previous studies have demonstrated that brucite grains with diameters ranging between 10 and 100µm (1.7×10^{-10} to 1.7×10^{-7} moles or 1.25×10^{-9} to 1.25×10^{-7} m^2, assuming spherical particles) are predicted to completely transform into magnesite in less than one year.[3,4,5]

While current project energy demands are being provided by the regional power grid, the low energy requirements of our electrochemical approach suggests that the future implementation of small-scale or on-site renewable power generation efforts (like solar) represents a promising and viable alternative.

References

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b. What is the current technology readiness level (TRL)? Please include performance and stability data that you've already generated (including at what scale) to substantiate the status of your tech.

TRL-4

Brucite is a well recognized source material for direct air capture via mineralization, since it directly converts CO_2 into a stable mineral (magnesite). The main bottleneck for the large-scale implementation of brucite-based CDR technologies, however, is the difficulty in sourcing the material, which is only available in limited quantities and from challenging locations (mines, tailings piles, etc.).

To address these needs, Minerali has validated the performance of our electrochemical brucite-based CDR technology on the scale of 200-Liter tanks at our experimental seawater facility. The results obtained from these initial validation studies have demonstrated that our CDR source material synthesis processes can yield kilogram quantities of brucite crystals with measured bulk yield purities >95%. These results demonstrate how Minerali has the unique ability to not only electrochemically precipitate large quantities of premium quality brucite, but also analyze and quantify CO_2 capture.

After the precipitated products have been collected and characterized for a given optimization experiment, their CO_2 capturing potentials are investigated. The final results of these analyses provide valuable information for further optimizing the mineral precipitation reaction processes in order to increase yield and product purity in an iterative fashion throughout the Frontier pre-purchase contract timeline and beyond.

Minerali, fully recognizing the commercial hurdles of optimizing product yield and precipitation and conversion kinetics, has pioneered a process for synthesizing premium quality source material for DAC through seawater electrolysis, and has a significant head start on known potential competitors.

c. Who are the key people at your company who will be working on this? What experience do they have with relevant technology and project development? What skills do you not yet have on the team today that you are most urgently looking to recruit?

Our collaborative and interdisciplinary team has already demonstrated the laboratory-scale feasibility of our approach, with current studies underway to optimize the electrochemical process for capturing CO_2 with brucite precipitates under various real-world conditions.

We have the background and real-world experience necessary to turn this technology into a viable permanent carbon capture and storage business. Future talent recruitment will focus on training on-site workers to operate brucite precipitation systems at scale. With the funds from a Frontier pre-purchase, Minerali will grow our team organically by recruiting from a pool of talented chemical, electrical, and materials engineers and logistics experts through our extensive peer and professional networks.

d. What is the total timeline of your proposal from start of development to end of CDR delivery? If you're building a facility that will be decommissioned, when will that happen?

Since we've already begun optimization and development, we expect that it will take 3 years (from Jan 2023 to Jan 2026) to deliver our committed amount of CDR to Frontier.

Modular systems will remain functional and ultimately be scaled for future projects.

e. What other revenue streams are you expecting from this project (if applicable)? Include the source of revenue and anticipated amount. Examples could include tax credits and co-products.

Brucite is a very useful commodity for improving the efficiency of fertilizers, which we will certainly tap-into as a supplementary source of revenue. Across the world, brucite colloids (white, powdery liquids) are used as a magnesium nutrient source for crops during the growing season in order to increase harvest yields, food quality, and plant resistance to diseases in adverse environmental conditions. As a fertilizer additive, brucite provides high magnesium content and large reactive surface area for plant uptake, making it a very effective resource for enhancing farming outputs that could become a lucrative co-product revenue stream to our primary CDR activities. To that end, Seacor Holdings (a wholly owned subsidiary of American Industrial Partners) has indicated interest delivering brucite to buyers of the raw material for fertilizer applications in the Caribbean, Brazil, and greater Latin America.

A secondary benefit of Brucite is its use in concrete production "co-benefit". This has the potential to produce revenue and also add incremental CDR benefit, none of which are currently being accounted for in our CDR amounts or TEA..

2. Durability

a. Describe how your approach results in permanent CDR (> 1,000 years). Include citations to scientific/technical literature supporting your argument. What are the upper and lower bounds on your durability estimate?

The conversion of brine-derived brucite into indefinitely stable carbonates is a game changer in the search for fast, efficient, and low-cost carbon mineralization for the following reasons:

- The reaction is extremely thermodynamically favored, so the storage of CO_2 is permanent (Kittrick et al. 1986; Sverjensky et al. 1984).
- The products of the reaction are readily verifiable using standard material characterization approaches, facilitating regulatory oversight.
- The public is more likely to accept mineralization as a viable long-term solution. The IPCC specifically commented that the "highly verifiable and unquestionably permanent" nature of mineralization is likely to lead to its greater public acceptance.
- The storage capacity of CO_2 via mineralization pathways is (theoretically) limitless.

- The seawater and brines that we propose to use for the production of these reactive mineralization materials are abundantly available resources, particularly in arid coastal settings (Gude et al. 2016; Mustafa et al. 2022; Jones et al. 2019).

b. What durability risks does your project face? Are there physical risks (e.g. leakage, decomposition and decay, damage, etc.)? Are there socioeconomic risks (e.g. mismanagement of storage, decision to consume or combust derived products, etc.)? What fundamental uncertainties exist about the underlying technological or biological process?

The solid-phase transformation of brucite into magnesite is physically durable and highly thermodynamically favored, meaning it will not decay or decompose.

Although substantial research indicates that hydrated brucite grains will completely transform to magnesite in under a year if left to dry under standard open air conditions, efficiency improvements that would occur within CO_2 reactors have still to be confirmed. The time required for brucite transformation magnesite could accelerate from one year down to days (or even hours) through the use of high efficiency CO_2 reactors, which Minerali plans to explore.

3. Gross Removal & Life Cycle Analysis (LCA)

a. Please articulate and justify the boundary conditions you assumed above: why do your calculations and diagram include or exclude different components of your system?

Depending on the source of magnesium (direct feed from desalination plants, for example), the long-term energy costs required for feeding our electrochemical reactors (via secondary pumps, for example) can be largely eliminated.

Furthermore, since the precipitated minerals are denser than water, no complex or energy-intensive product harvesting infrastructure is required since the precipitated product can simply be gravity drained from our electrochemical reactors. In addition, depending on the location of our electrochemical facility, the precipitated brucite can be locally used, largely reducing or eliminating product transportation costs.

4. Measurement, Reporting, and Verification (MRV)

Section 3 above captures a project's lifecycle emissions, which is one of a number of MRV considerations. In this section, we are looking for additional details on your MRV approach, with a particular focus on the ongoing quantification of carbon removal outcomes and associated uncertainties.

a. Describe your ongoing approach to quantifying the CDR of your project, including methodology, what data is measured vs modeled, monitoring frequency, and key assumptions. If you plan to use an existing protocol, please link to it. Please see [Charm's bio-oil sequestration protocol] for reference, though note we do not expect proposals to have a protocol at this depth at the prepurchase stage.

Modern characterization tools will be used to quantify brucite and magnesium carbonate yield, purity, and CDR at biweekly time intervals over the duration of the proposal. In this way, we will be able to characterize and measure brucite-based CDR over in a more consistent and verifiable fashion than has been reported previously.

b. How will you quantify the durability of the carbon sequestered by your project discussed in 2(b)? If direct measurement is difficult or impossible, how will you rely on models or assumptions, and how will you validate those assumptions? *(E.g. monitoring of injection sites, tracking biomass state and location, estimating decay rates, etc.)*

Because the carbon-captured mineral phase (magnesite) exhibits distinctive compositional and spectroscopy signatures, the percent of brucite converted to magnesite as a function of time can easily be quantified using well established in-house materials characterization approaches.

c. Will this project help advance quantification approaches or reduce uncertainty for this CDR pathway? If yes, describe what new tools, models or approaches you are developing, what new data will be generated, etc.?

Yes, in the following ways:

- Optimization of the conditions for precipitation of crystallographically pure product.
- Design and implementation of large volume modular systems for brucite production.
- Identification of the key environmental parameters for carbon capture (e.g. humidity, temperature, pH, etc.).
- Integration of magnesite as a secondary cementitious material in concrete.
- Publication and dissemination of data and results on direct air capture using brucite as a source material.

d. Describe your intended plan and partners for verifying delivery and registering credits, if known. If a protocol doesn't yet exist for your technology, who will develop it? Will there be a third party auditor to verify delivery against that protocol or the protocol discussed in 4(a)?

Early stage plans: We will verify the fulfillment of CDR commitments and register carbon credits based on the results of our biweekly in-house sample analyses, which will serve as proxies for the direct air capture performance of our terrestrial precipitates.

5. Cost

We are open to purchasing high-cost CDR today with the expectation the cost per tonne will rapidly decline over time. The questions below are meant to capture some of the key numbers and assumptions that you are entering into the separate techno-economic analysis (TEA) spreadsheet (see step 4 in Applicant Instructions). There are no right or wrong answers, but we would prefer high and conservative estimates to low and optimistic. If we select you for purchase, we'll work with you to understand your milestones and their verification in more depth.

a. What aspects of your cost analysis are you least confident in?

> Cost of transportation and land management of brucite; we assumed 100 miles of transport by rail.

b. What is one thing that doesn't exist today that would make it easier for you to commercialize your technology? (e.g., improved sensing technologies, increased access to X, etc.)

> A digital trading and exchange platform for brucite and the embodied carbon in magnesite.

6. Public Engagement

In alignment with Frontier's Safety & Legality criteria, Frontier requires projects to consider and address potential social, political, and ecosystem risks associated with their deployments. Projects with effective public engagement tend to:

- Identify key stakeholders in the area they'll be deploying
- Have mechanisms in place to engage and gather opinions from those stakeholders, take those opinions seriously, and develop active partnerships, iterating the project as necessary

The following questions help us gain an understanding of your public engagement strategy and how your project is working to follow best practices for responsible CDR project development. We recognize that, for early projects, this work may be quite nascent, but we are looking to understand your early approach.

a. Going forward, do you have changes to your processes for (a) and (b) planned that you have not yet implemented? How do you envision your public engagement strategy at the megaton or gigaton scale?

> Design parameters of our system are based on affordability and simplicity of deployment to enable global use. We envision positive responses from the public and local engagement relative to other more complex approaches.

7. Environmental Justice[2]

As a part of Frontier's Safety & Legality criteria, Frontier seeks projects that proactively integrate environmental and social justice considerations into their deployment strategy and decision-making on an ongoing basis.

a. What are the potential environmental justice considerations, if any, that you have identified associated with your project? Who are the key stakeholders? Consider supply chain impacts, worker compensation and safety, plant siting, distribution of impacts, restorative justice/activities, job creation in marginalized communities, etc.

> From an ecology and ecosystem services perspective, the partially magnesium-depleted brines from the brucite synthesis process can be easily diverted into existing desalination brine treatment processes.
>
> In the future, another avenue for leveraging our technology is to mineralize the CO_2 from harmful flue gas streams at industrial plants that pollute and create heat issues for low-income coastal urban communities.

b. How do you intend to address any identified environmental justice concerns and / or take advantage of opportunities for positive impact?

> Minerali will only operate at desalination facilities whose brine outflow processes have been vetted, tested, and permitted by the US EPA.
>
> It is of utmost importance to us that Minerali's operations create net benefit for society. Any integration of our technology into an existing desalination plant will require that brine effluents entering water bodies be of adequate water quality.

8. Legal and Regulatory Compliance

a. What legal opinions, if any, have you received regarding deployment of your solution?

> None at this time.

b. What permits or other forms of formal permission do you require, if any, to engage in the research or deployment of your project? What else might be required in the future as you scale? Please clearly differentiate between what you have already obtained, what you are currently in the process of obtaining, and what you know you'll need to obtain in the future but have not yet begun the process to do so.

> Technology may be subject to licensing and terms and conditions set by such future agreement.

[2] For helpful content regarding environmental justice and CDR, please see these resources: C180 and XPRIZE's Environmental Justice Reading Materials, AirMiners Environmental and Social Justice Resource Repository, and the Foundation for Climate Restoration's Resource Database

c. Is your solution potentially subject to regulation under any international legal regimes? If yes, please specify. Have you engaged with these regimes to date?

No.

Application Supplement: DAC

(Only fill out this supplement if it applies to you)

Note: these questions are with regards only to air capture: e.g. your air contactors, sorbents or solvents, etc. Separately, there exist Geologic Injection and CO_2 Utilization supplements. We anticipate that most companies filling out this DAC supplement should ALSO fill out one of those supplements to describe their use of the CO_2 stream that's an output of the capture system detailed here.

Capture Materials and Processes

1. Several direct air technologies are currently being deployed around the world. Why does your DAC technology have a better chance to scale and reach low cost than the state of the art?

Our technology is a simple, modular, inexpensive, and easily scalable point-source carbon capture system that involves exposing CO_2-laden gas (in this case, in ambient open air) to brucite crystals that chemically mineralize CO_2 to form magnesite for permanent low-cost terrestrial storage. One of the greatest advantages of our technology is that it can be rapidly deployed at any existing desalination facility (for use with waste brines), without the need for extensive infrastructure modifications. With comparatively low power requirements, it can be readily adapted for use with renewable energy sources like solar or wind, further reducing the carbon footprint of the facility. Furthermore, its highly modular nature means that small pilot plants can be quickly fabricated and then scaled up as needed. As for maintenance costs, the technology employs low cost and readily available components, reducing maintenance costs and minimizing downtime.